National Observatory of Athens (NOA)

INSTITUTE FOR ASTRONOMY, ASTROPHYSICS, SPACE APPLICATIONS & REMOTE SENSING
(formerly INSTITUTE OF ASTRONOMY & ASTROPHYSICS)
National Observatory of Athens

IAASARS

# ENERGETIC PARTICLE OBSERVATIONS CLOSE TO THE SUN BY SOLAR ORBITER AND PARKER SOLAR PROBE

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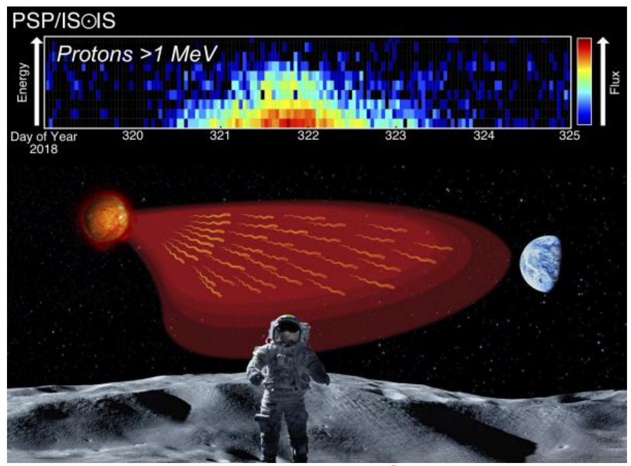
EGU

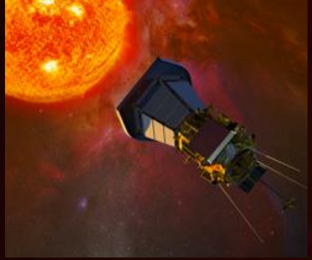
ISOIS Parker Solar Probe
NASA · GSFC · JPL · Caltech · Princeton · SwRI · APL · UNH · U-Az · U-Del
ENERGETIC PARTICLES




Energetic Particle Detector
epd
SOLAR ORBITER

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany

37th International Cosmic Ray Conference
12–23 July 2021




D. J. McComas(2)
J. Rodríguez-Pacheco (3)
N. Schwadron (4)
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G. C. Ho (6)
& the **Solar Orbiter/EPD and Parker Solar Probe/ISOIS teams**

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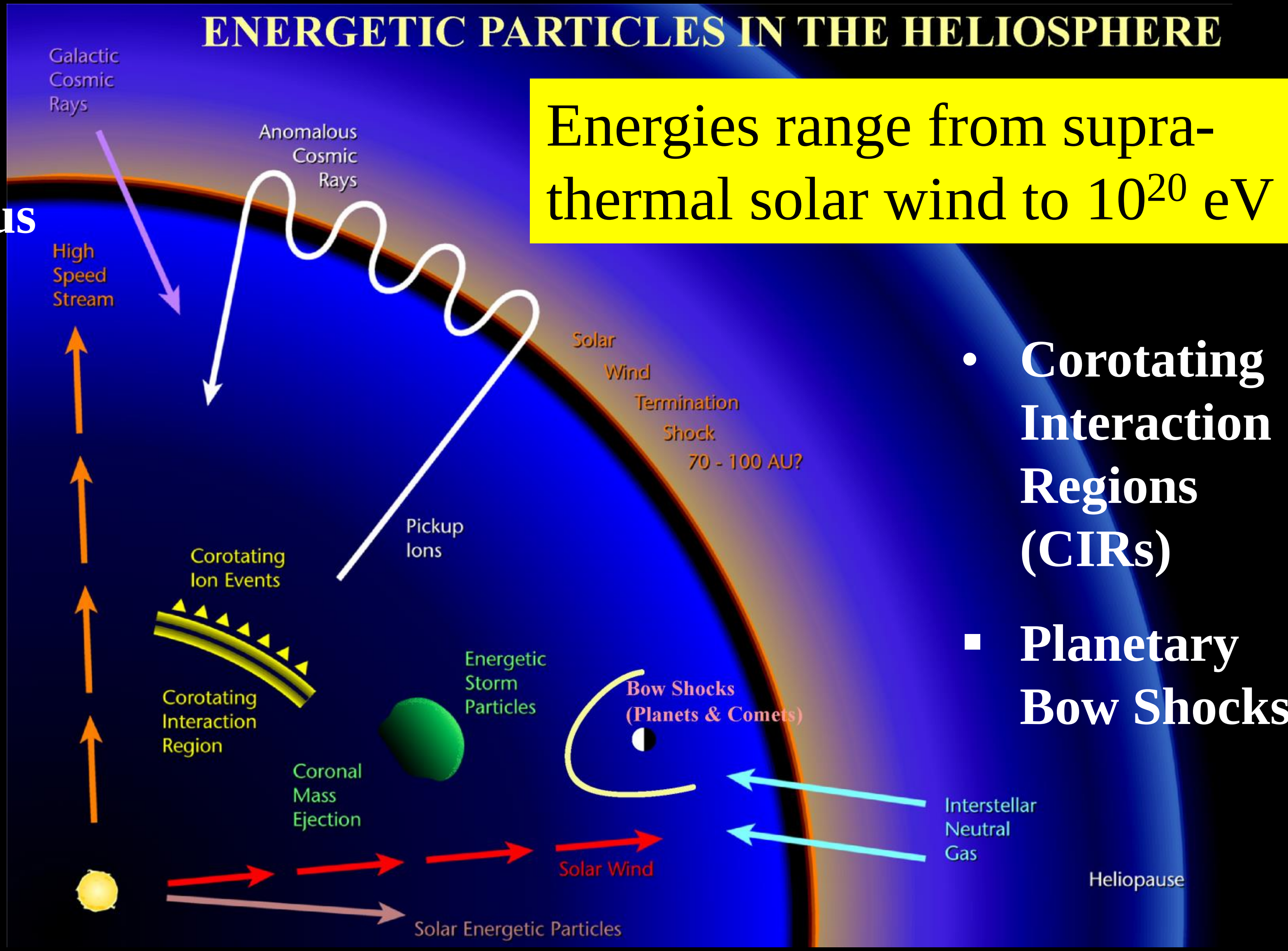
- Galactic Cosmic Rays (GCRs)
- Anomalous Cosmic Rays (ACRs)
- Solar Energetic Particles (SEPs)
- Energetic Storm Particles (ESPs)



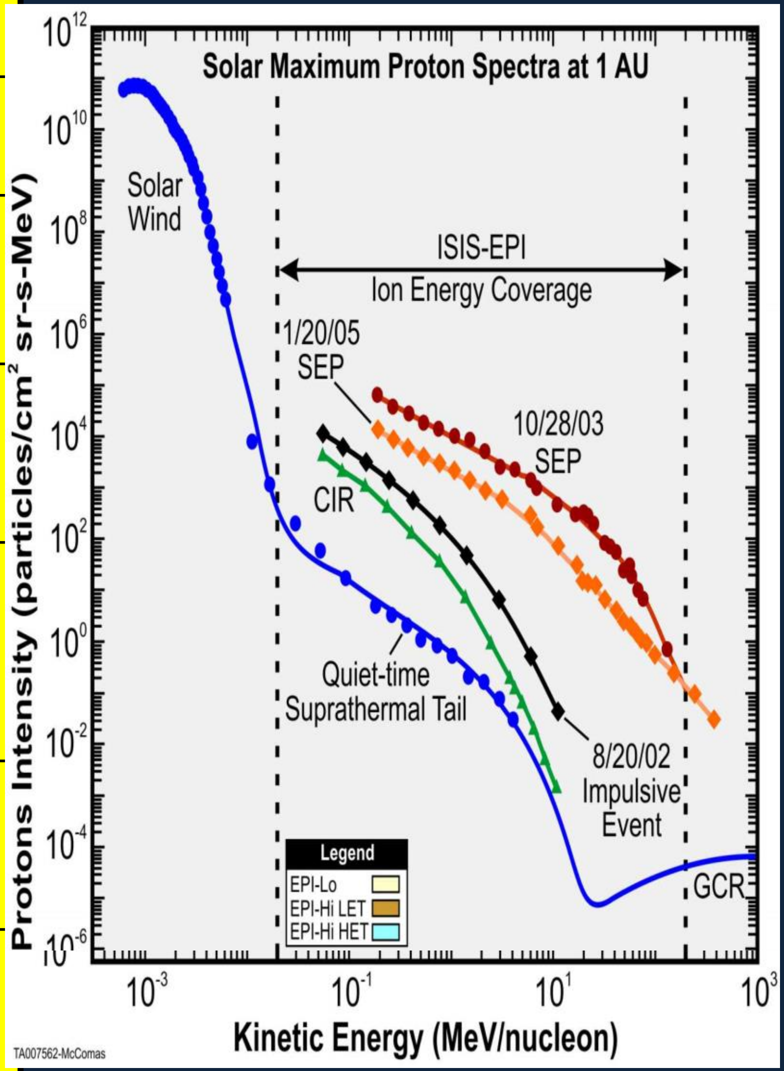

Energies range from supra-thermal solar wind to $10^{20}$ eV

- Corotating Interaction Regions (CIRs)
- Planetary Bow Shocks

# Overview of Particle Populations

| Particle Population | Temporal scales | Spatial scales | Energy range | Acceleration mechanisms |
|---|---|---|---|---|
| GCRs | continuous | global | GeV ---> TeV | Diffusive shock |
| ACRs | continuous | Global | 10-100 MeV | Diffusive shock, shock drift, or other? |
| CIRs | 27 days | Large-scale | keV ---> 10 MeV | Diffusive shock, shock drift, stochastic |
| SEPs | δ | δ | keV ---> GeV | Reconnection, stochastic, selective heating, shock |
| ESPs | days | extended | keV ---> 100 MeV | Diffusive shock, shock drift, stochastic |
| Planetary bow shocks | continuous | local | keV ---> MeV | Diffusive shock, shock drift |

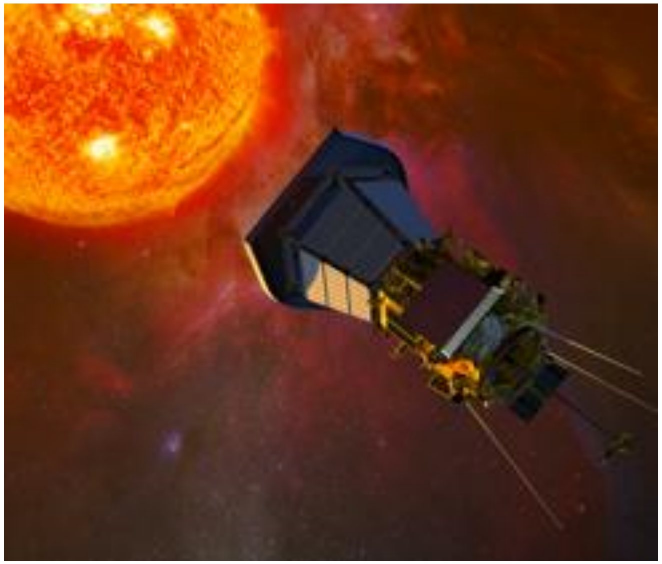
*Desai 2019*



# Pioneering Solar Missions – Key Open Questions
# Unique measurements In The Inner Heliosphere

*Malandraki and Crosby 2018*

## Parker Solar Probe



Launch: 4 August 2018
Perihelion up to~**9 $R_S$**

Integrated Science Investigation of the Sun (**ISOIS**)

PI: Prof. Dave McComas (USA)

*(Science Collaborator)*

## Solar Orbiter

Launch: 10 February 2020
Perihelion up to~**0.3 AU**

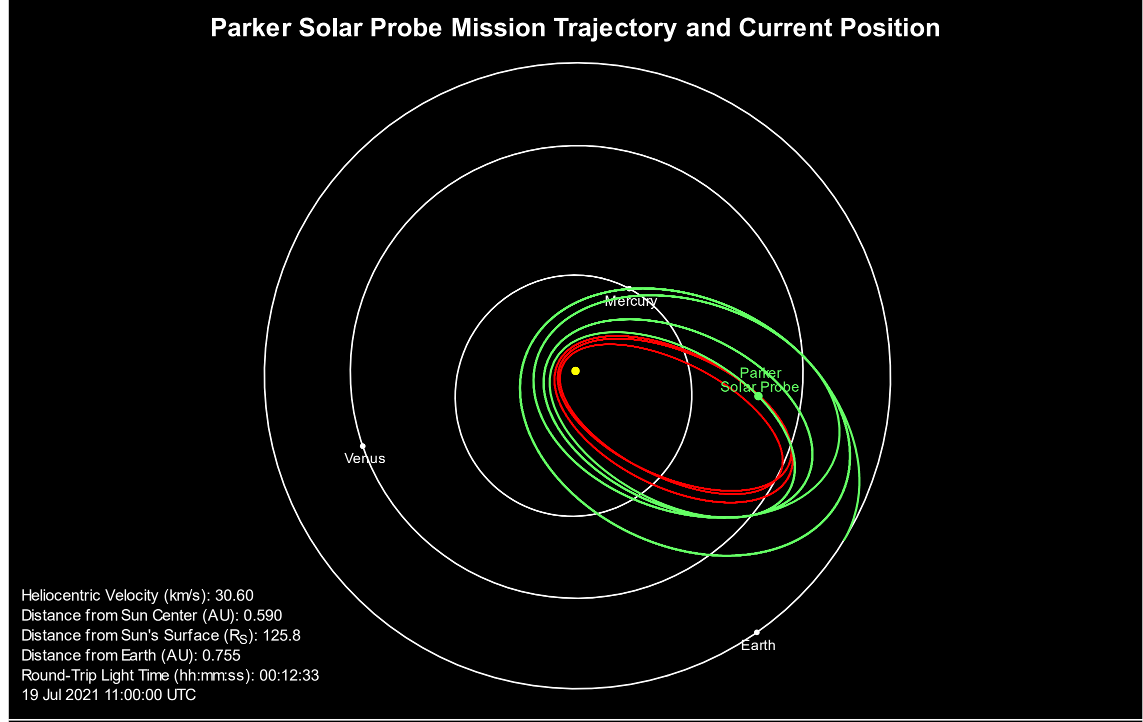
Energetic Particle Detector (**EPD**)

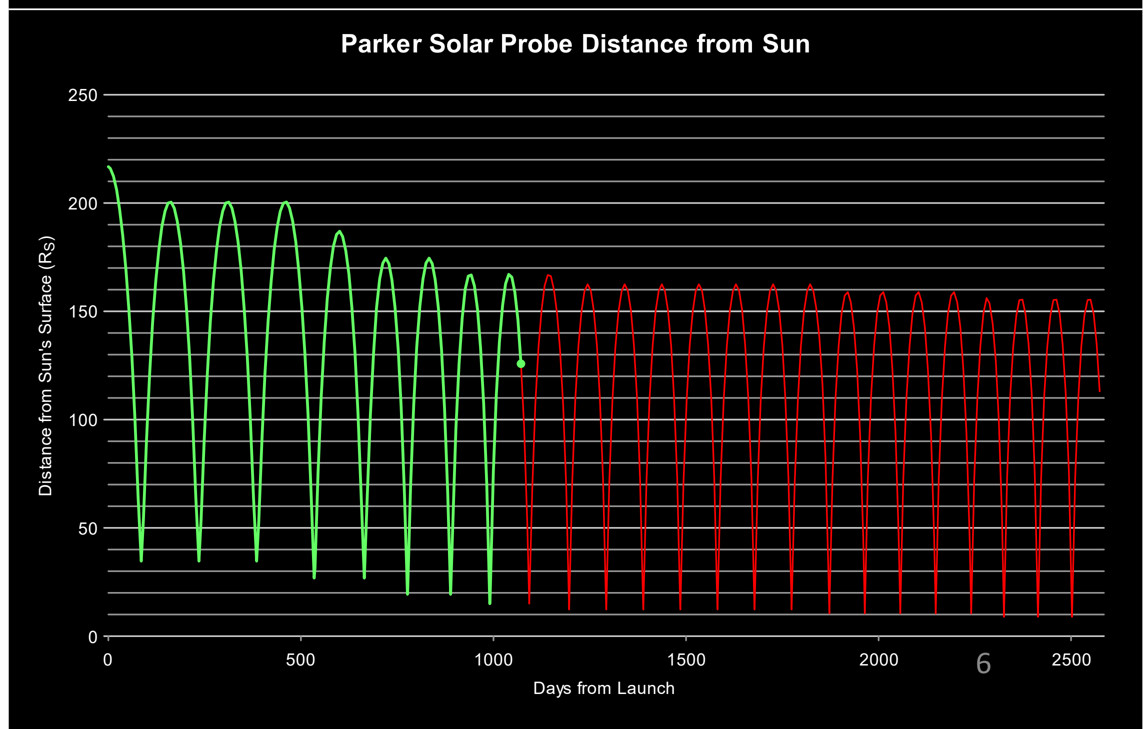
PI: Prof. Javier Rodriguez-Pacheco (Spain)
Co-PI: R. Wimmer-Schweingruber (Germany)

*(Co-Investigator)*

Parker Solar Probe Mission Trajectory and Current Position (19 July, 2021)

PSP in a highly elliptical orbit around the Sun repeatedly plunges closer to the Sun than any previous s/c!



# Integrated Science Investigation of the Sun (ISOIS) Energetic particle investigation

McComas et al., SSR 2016

Hill et al. 2017, EPI-Lo

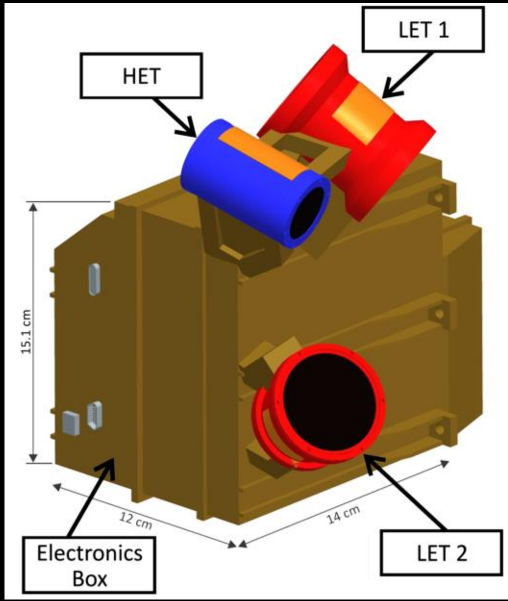
Wiedenbeck et al. 2017, EPI-Hi

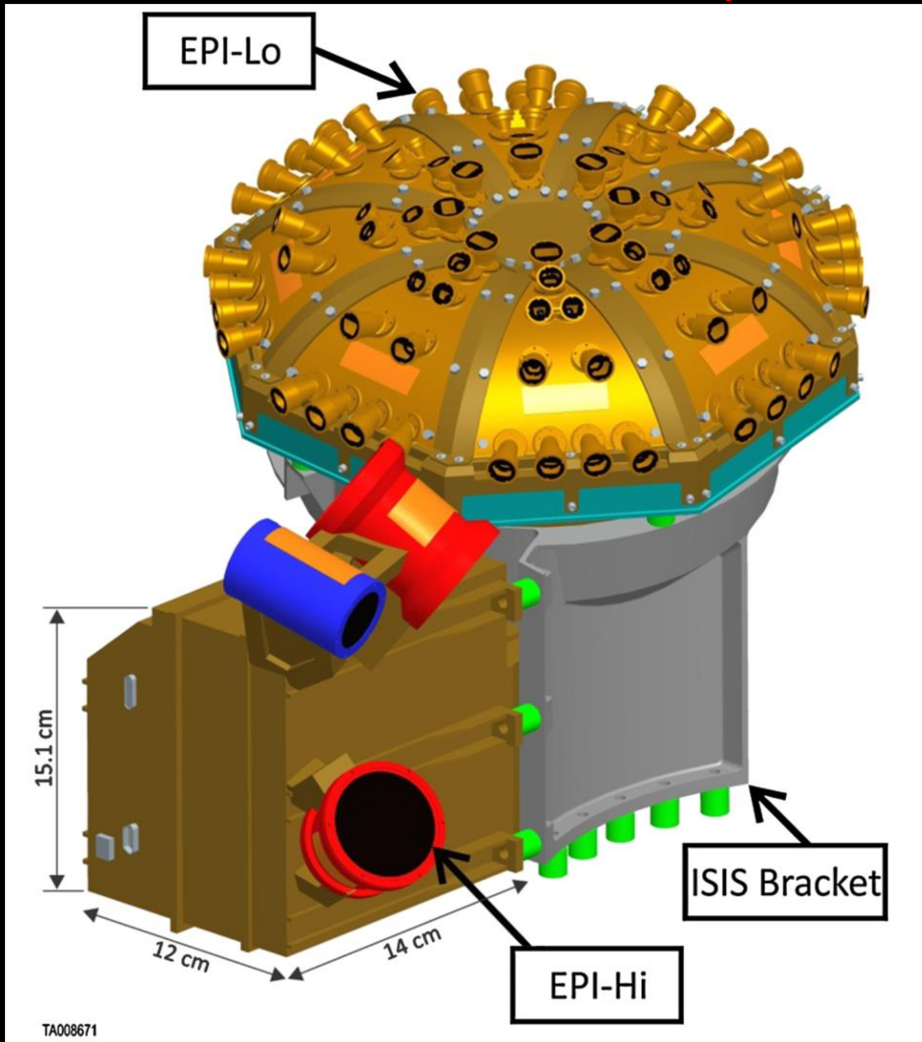
Energy spectra, anisotropy and composition of suprathermal and solar energetic ions ~0.02-200 MeV /nuc

Energy spectra and arrival direction of ~0.025-6 MeV electrons.

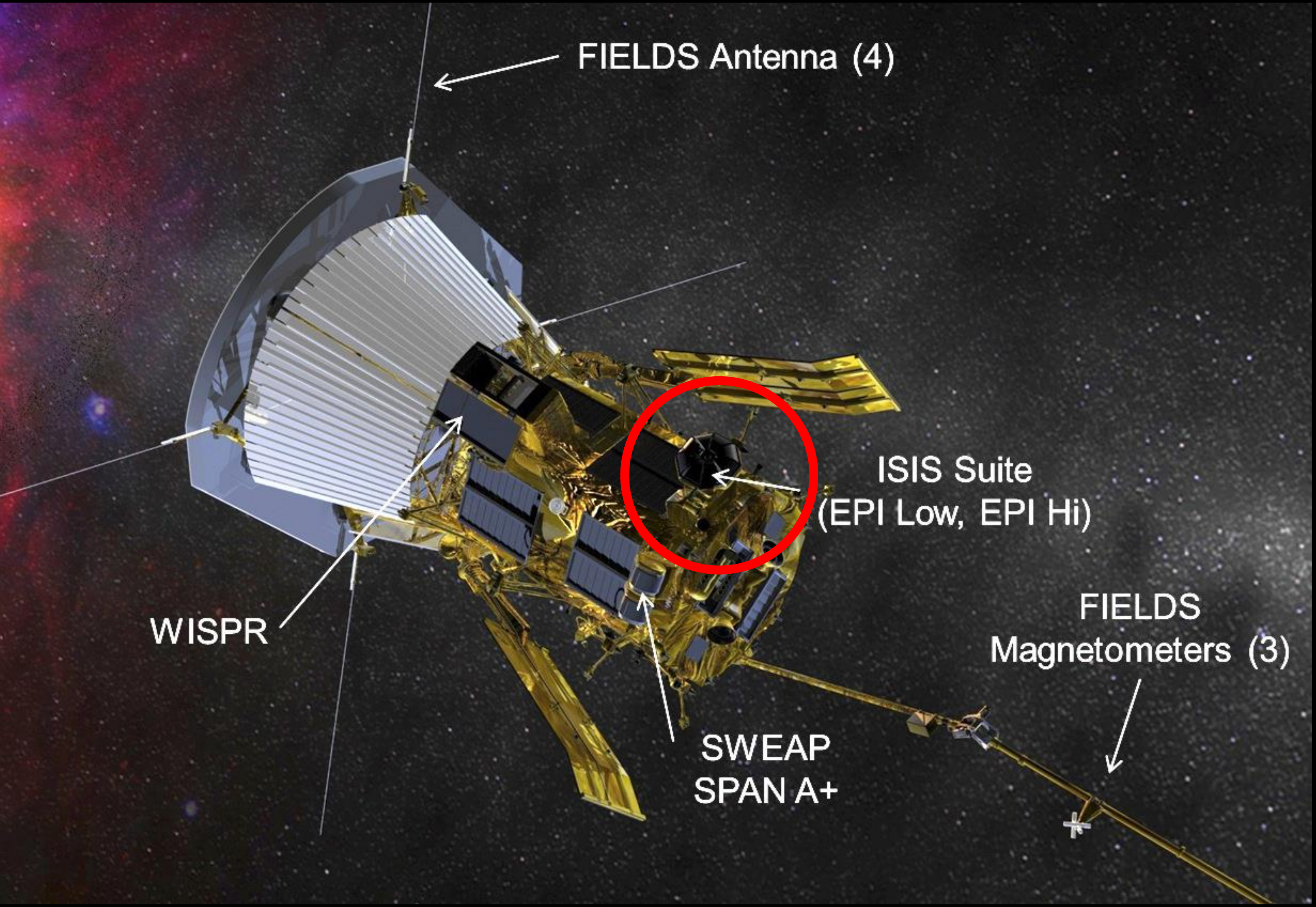
2 complementary instruments:
Energetic Particle Instrument-Low Energy (EPI-Lo), & -High Energy (EPI-Hi)

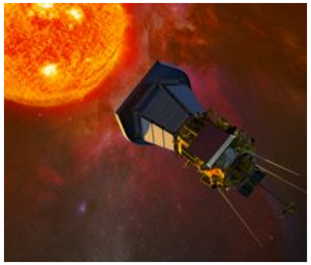
EPI-Hi Mechanical Design



# ISOIS Ram Facing side of S/C





# ISʘIS Science Goals

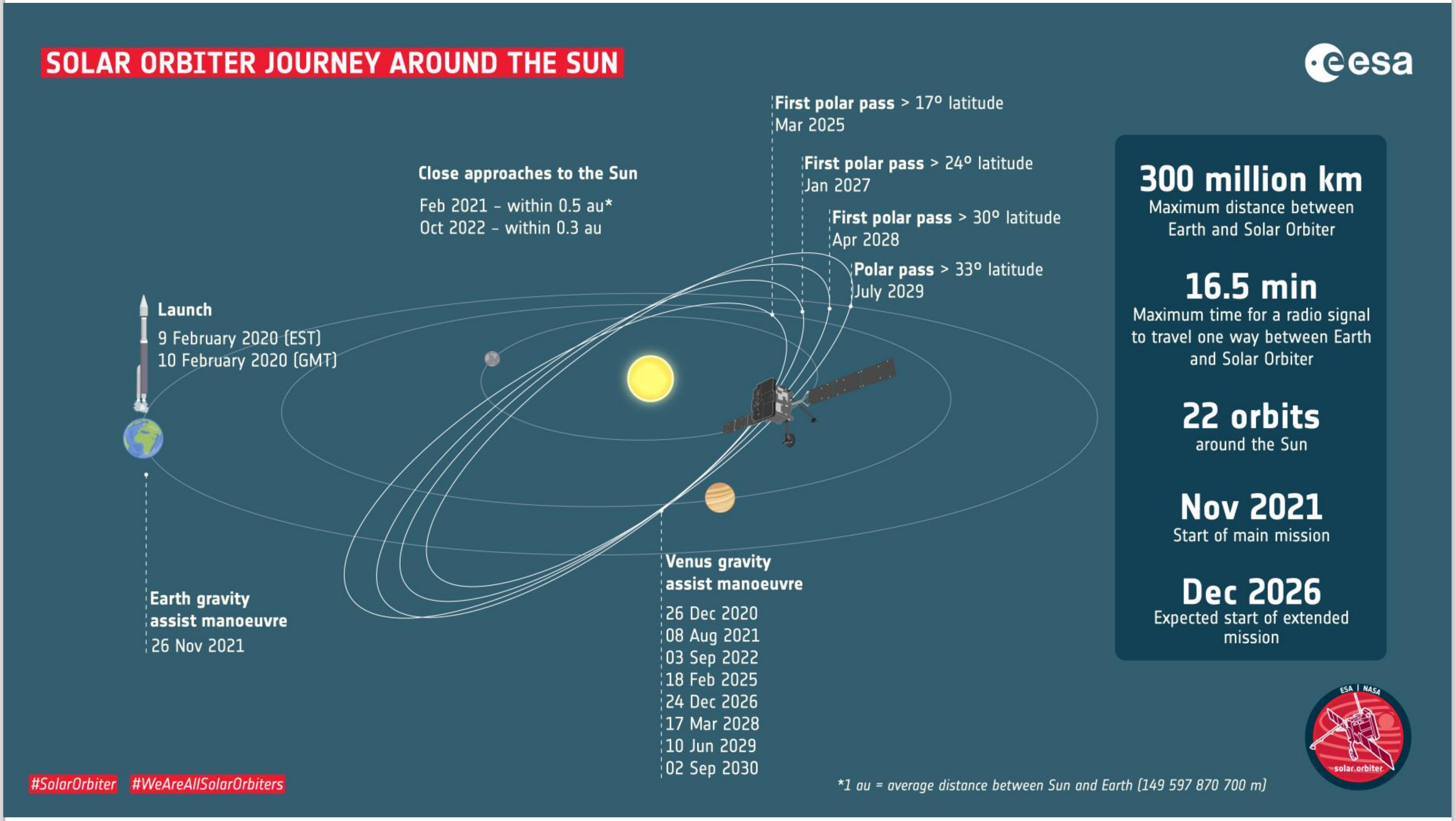
- **Origin:** Define the seed populations and physical conditions necessary for energetic particle acceleration

- **Acceleration:** Determine the roles of shocks, reconnection, waves, and turbulence in accelerating energetic particles

- **Transport:** Reveal how energetic particles propagate from the corona out into the heliosphere

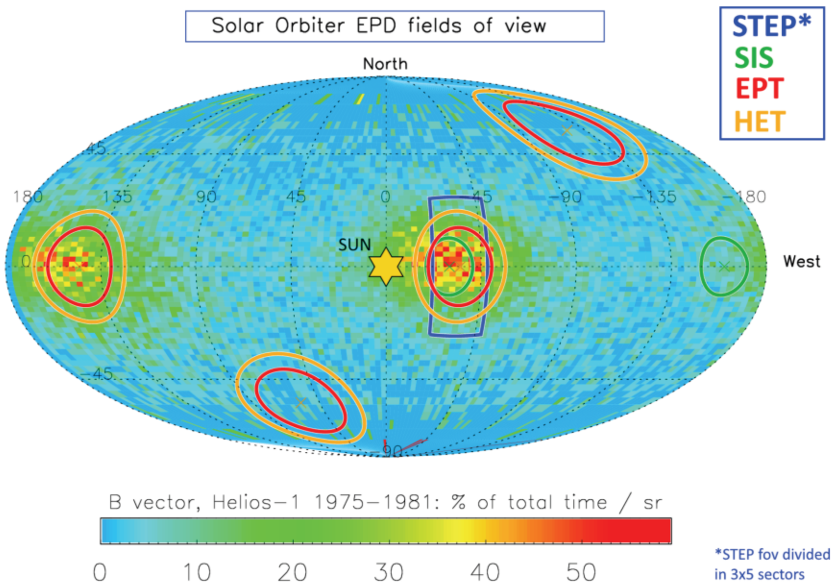
*McComas et al., SSR 2016*

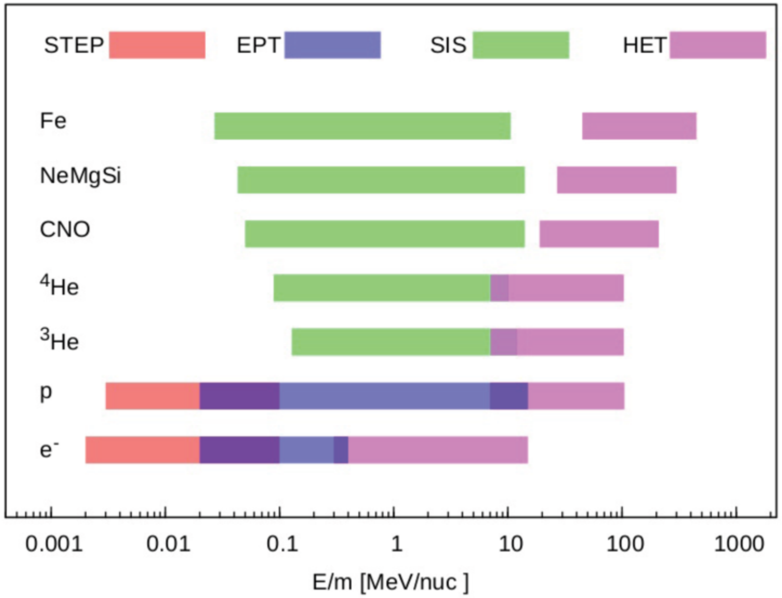
# SOLAR ORBITER MISSION



# Energetic Particle Detector (EPD)

- Wide energetic and compositional coverage to study different heliospheric particle populations. Several FoV provide directional information




- Time Resolution: up to 1 s !!!

***Rodríguez-Pacheco,…,Malandraki et al. 2020, A&A***
***The Solar Orbiter Mission***

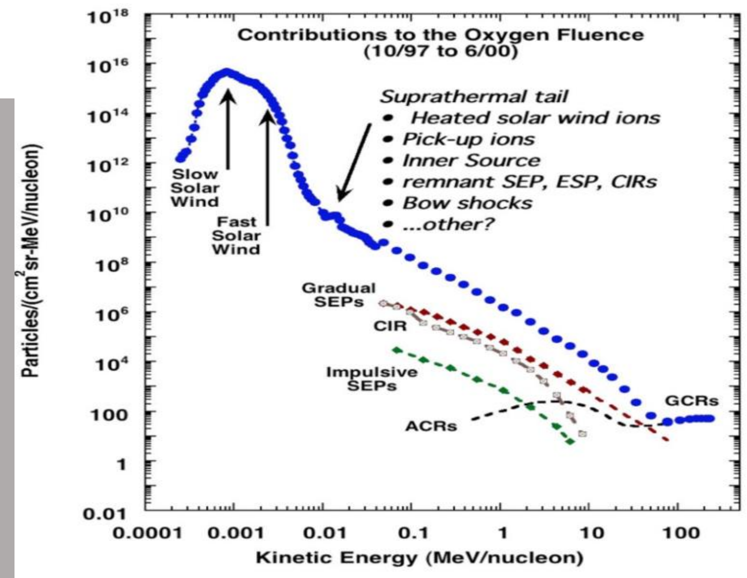
*Javier Rodríguez-Pacheco, 2018*

# How do solar eruptions produce energetic particle radiation that fills the heliosphere?

This can be broken down into several key topics:

1. SEP seed populations
2. Injection, acceleration and release processes of SEPs
3. SEP transport

*Mewaldt, 2001*




***1. What are the seed populations for energetic particles?***

***2. How and where are energetic particles accelerated at the Sun?***

***3. How are energetic particles released from their sources and distributed in space and time?***

***Müller et al. 2013, Müller et al 2020***

# The importance of SEP measurements close to the Sun

*Javier Rodríguez-Pacheco, 2018*

***Rodríguez-Pacheco,…,Malandraki et al. 2020, A&A***
***The Solar Orbiter Mission***

- The pioneering Helios observations highlighted the importance of in-situ measurements close to the Sun, where much of the crucial physics related with solar activity takes place

- By travelling close to the Sun, Solar Orbiter will observe unevolved small-scale structures
- SEPs close to the Sun are less disturbed by transport effects, → key observations to unveil particle acceleration sites, acceleration mechanisms and seed populations

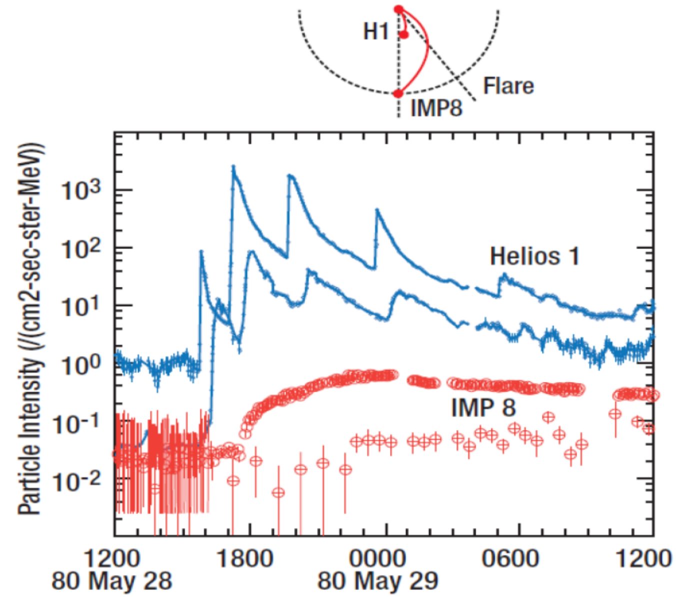
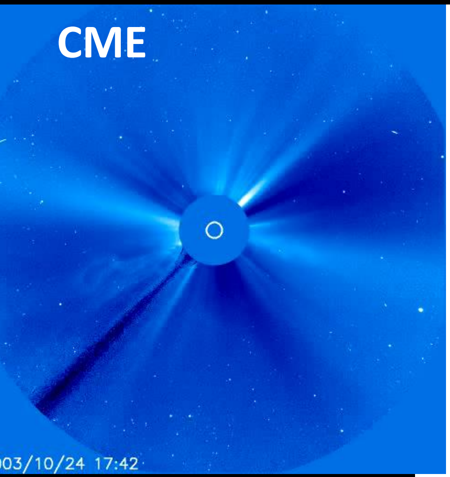
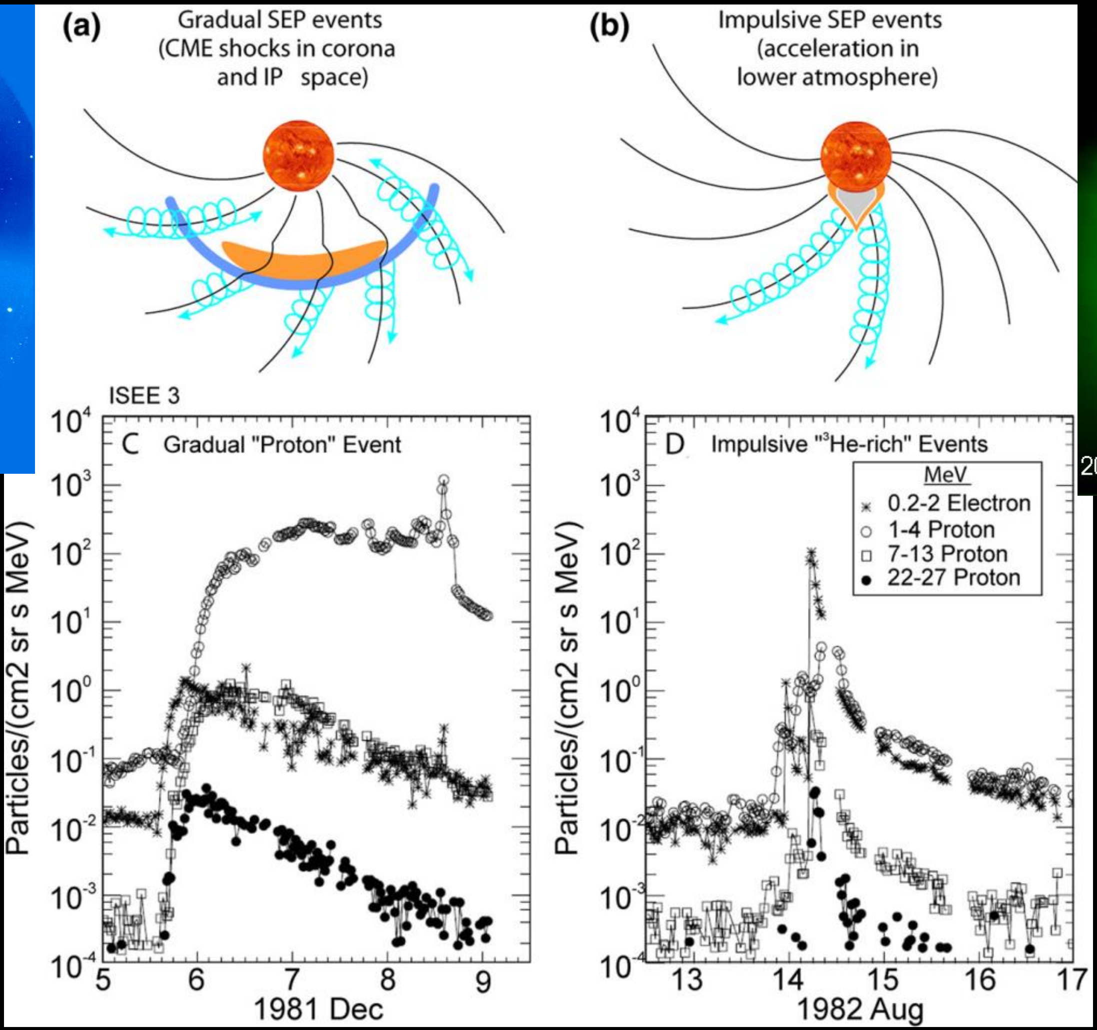


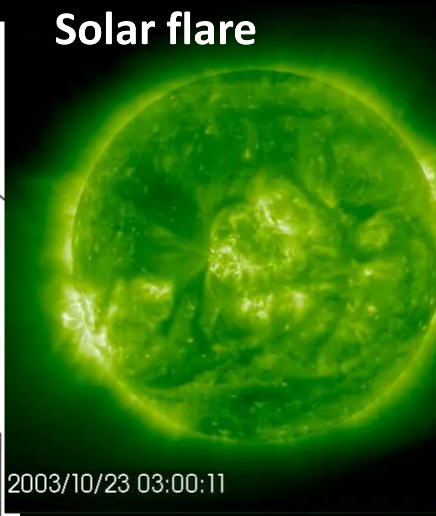

**Figure 1-1.** Electron and alpha particle time profiles recorded by Helios-1 at 0.3 AU and by IMP-8 at 1.0 AU during a series of impulsive particle events on 1980 May 28. Whereas Helios-1 observed multiple injections, no such structures can be resolved in the intensity-time profile at 1 AU. If both spacecraft were observing the same events (and this is not certain), then this plot vividly illustrates both the effects of radial and longitudinal transport inside 1 AU and the need for observations as close to the Sun as possible [Wibberenz and Cane, 2006].

*McComas et al., 2007*

# Solar Energetic Particle Events



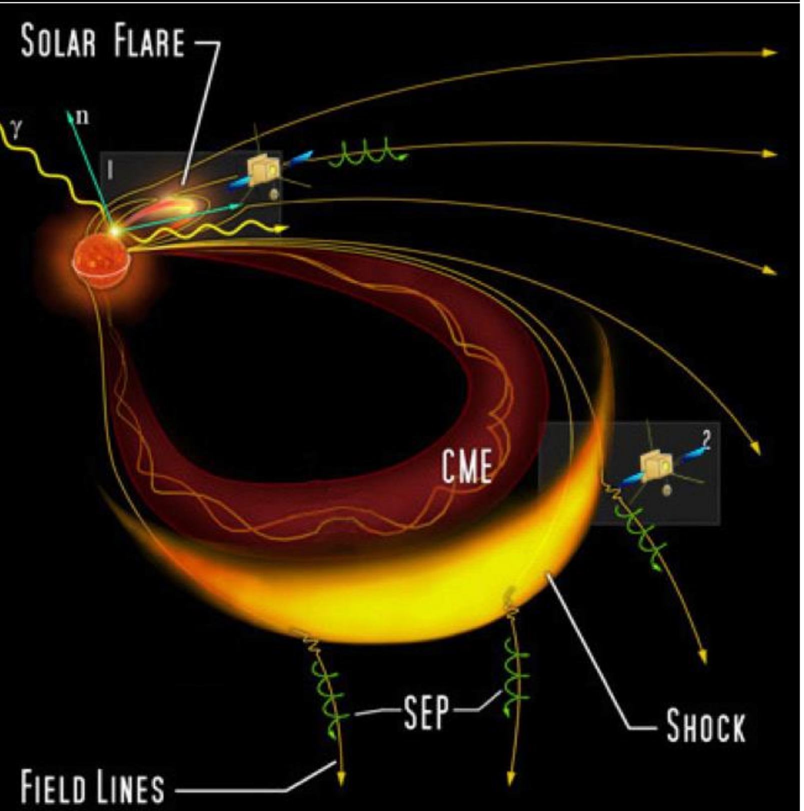



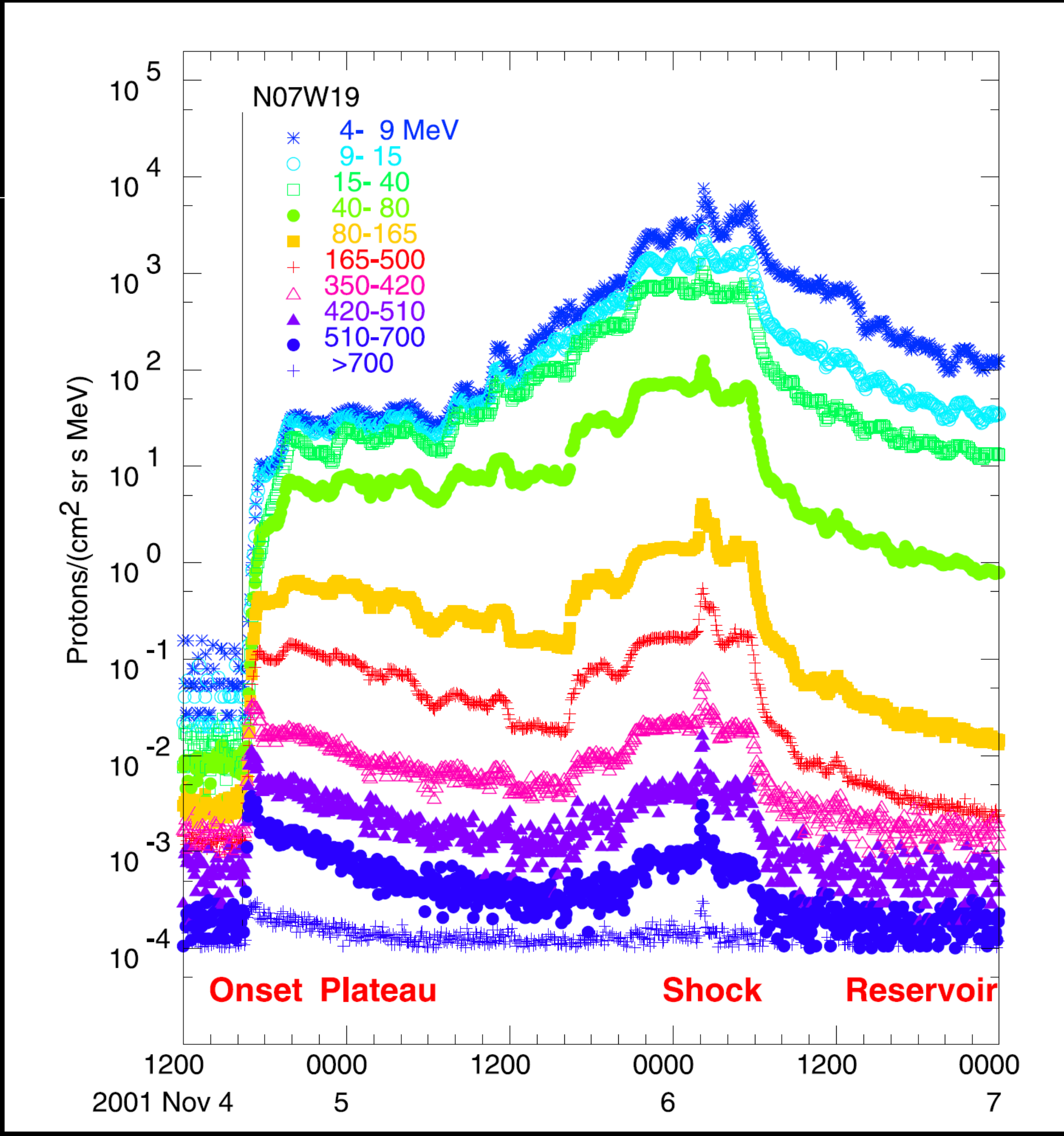

Large Gradual SEP events accelerated at CME-driven shocks

$^{3}$He-rich SEP events accelerated during solar flares via magnetic reconnection

*Malandraki & Crosby, 2018,*
*Springer Astrophysics and Space Science Library (ASSL) series: 'Solar Particle Radiation Storm Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and beyond'*

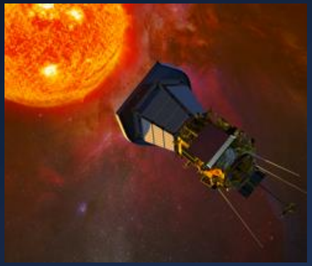
# Energetic Storm Particles: SEPs from CME shocks



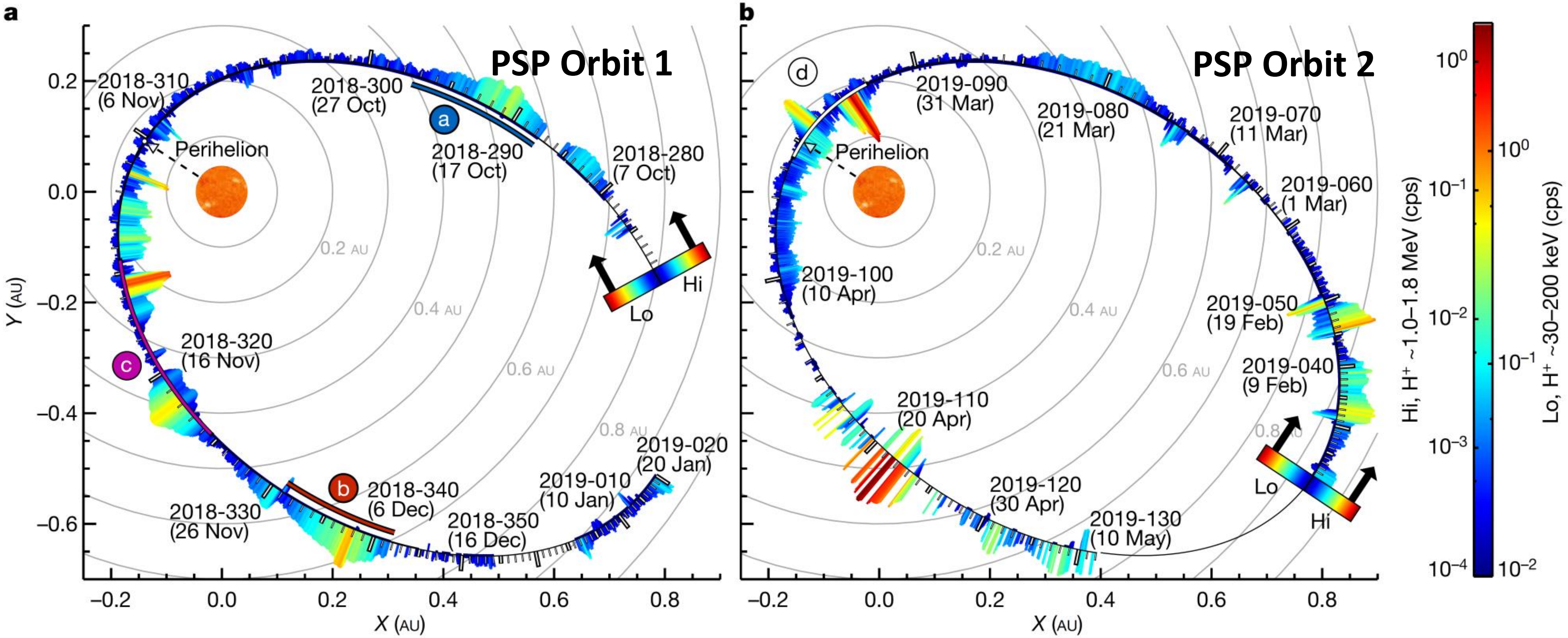




*Solar Orbiter Red Book 2011*

*Reames 2013*

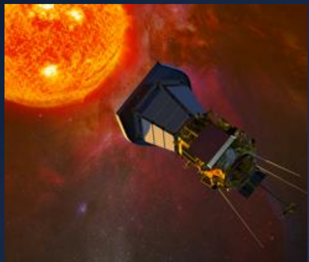


# Overview of First Two PSP Orbits



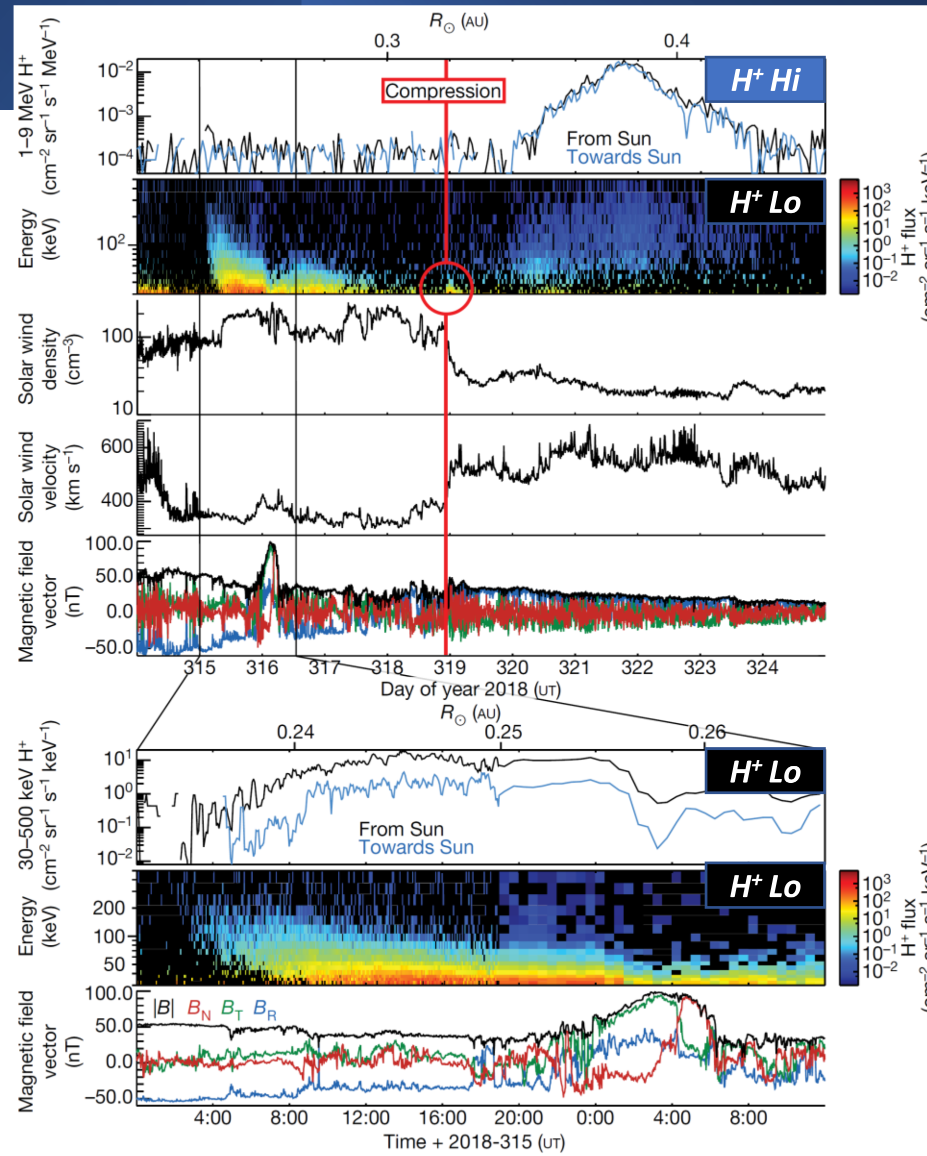

**McComas,…,Malandraki et al. 2019, *Nature***

ISOIS observed a number of interesting energetic particle events over a range of radial distances during the first two PSP orbits including CIR/SIR-related events (a,b), impulsive SEP events driven by acceleration near the Sun (d) and events related to ICMEs (c)

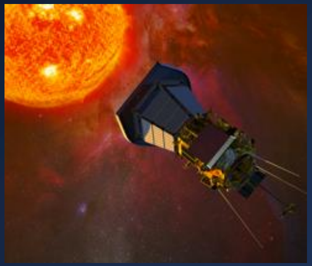


# CME-related SEP event near First Encounter

- ISOIS observations show an SEP event starting early on 2018-315 and extending to about when an ICME arrived at PSP on 2018-316. The event was only observed at **low energies**.
- The event is highly anisotropic (outward from the Sun) and exhibits velocity dispersion
- Time-energy slope (g): a path length was estimated which is longer than that of the Parker spiral from PSP at **~0.25 AU**, possibly explained by a longer pathlength associated with magnetic field 'switchbacks' observed by PSP in situ (Bale et al. 2019)
- The event **was not observed at 1 AU**, so such small events may be observable near to the Sun and therefore much more common than previously thought

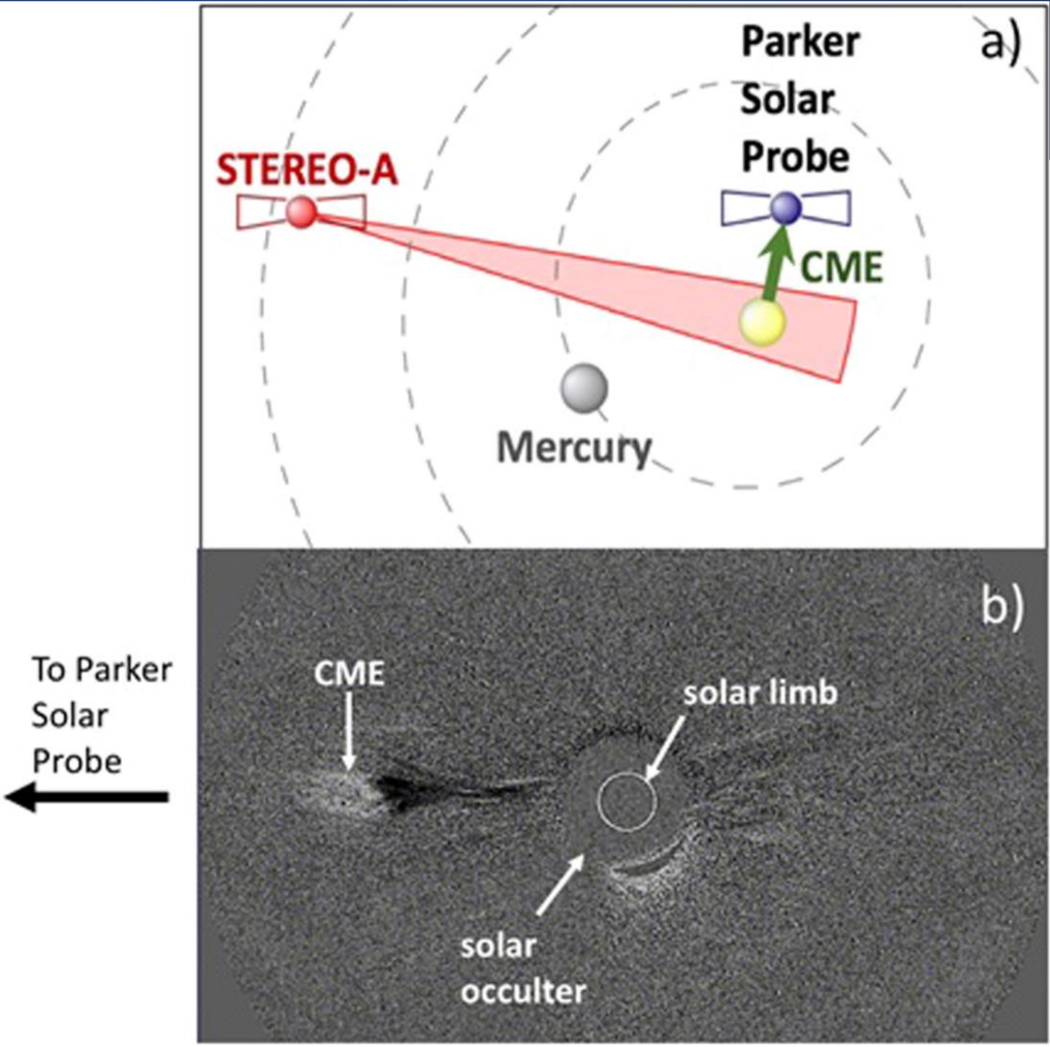



**McComas,…,Malandraki et al. 2019, *Nature***



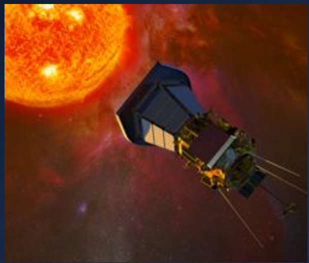
# CME-related SEP event near First Encounter

- No CME identified in SoHO/LASCO images because PSP in opposition with the Earth. However, **PSP was located at quadrature with STA.**
- White-light STA/COR-2 observed the eruption of a CME at 3Rs off the east limb if the Sun (as viewed from STA) near 18:00 UT on 2018-314 (Nov 10). The CME observed roughly propagating in the direction of PSP. CME speed **< 400 km/s**, slow, derived by STA imaging
- Early modeling indicates that there was no shock magnetically connected to the s/c. But a Q-Perp sub-critical shock (Mach number <3) could have formed over an extended region of the FR and may have accelerated the protons measured by PSP




Running-difference image of the CME at 02:39 UT on 2018 Nov 11 by COR-2

**McComas,…,Malandraki et al. 2019, *Nature***

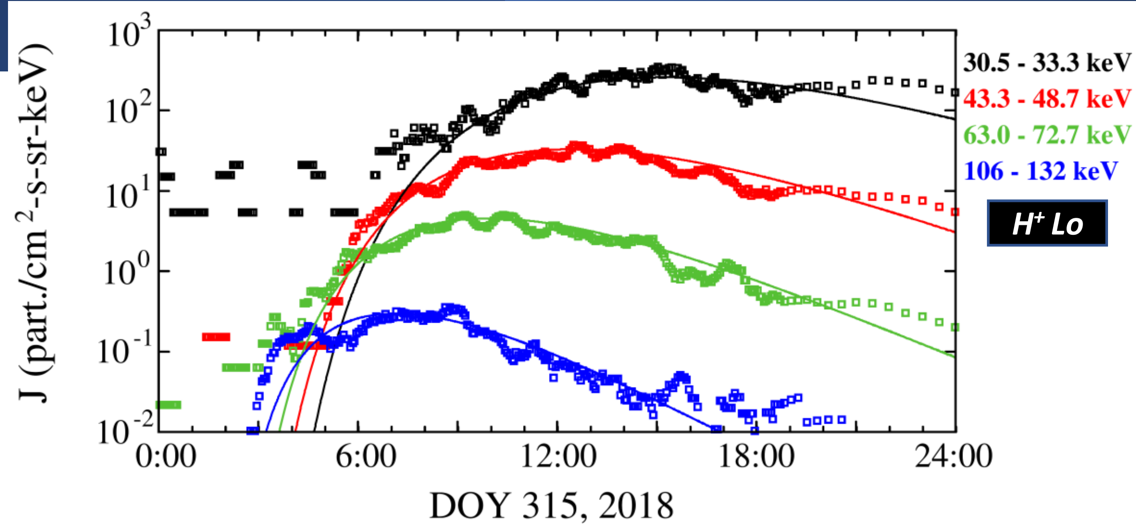


# CME-related SEP event near First Encounter

- Onset time of the earliest arriving **>100 keV** ions consistent with their origin at the CME when it was @7.4 $R_\odot$ and moving without scattering to PSP. L (**ions > 100 keV**) = **0.21 AU** (45 $R_\odot$).

- **Ions < 50 keV arrive later, by about 2-4 hr**, compared with the time expected from scatter-free transport L (**ions < 50 keV**)=**0.32-0.38 AU** (~70-80 Rs) almost x 2

- Solved the Parker transport equation (Parker, 1965) to model and fit the observed ion fluxes (30-132 keV $n^{-1}$), assuming a source coming with the CME. Model agrees with the observations **→ the delay in the arrival of the l-e ions is the result of scattering in the IP medium**




- **Symbols**: ion flux measured by EPI-Lo vs time. **Curves:** results from the calculation of the Parker transport equation. Comparison reasonable but not for the early part of the event. Expected since the Parker equation assumes isotropic distributions (not consistent with the observations during the initial rise phase of the event)

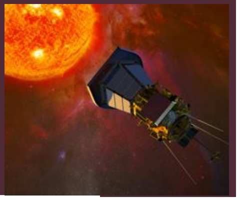
- Parallel diffusion coefficient that best fits the data:

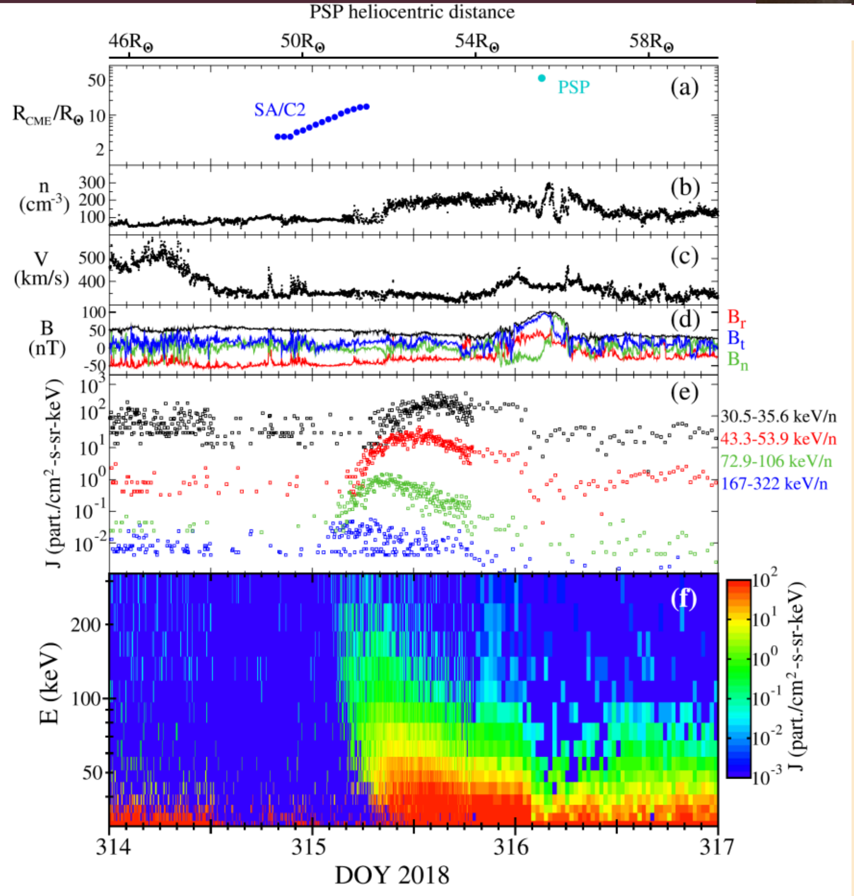
$$\kappa = 2.7 \times 10^{17} (r/r_0)^2 (E/E_0)^{9/8}$$

where $\mathbf{r_0=7.4\ R_\odot}$ and $\mathbf{E_0=10\ keV}$

**Giacalone et al. 2020 *ApJS***

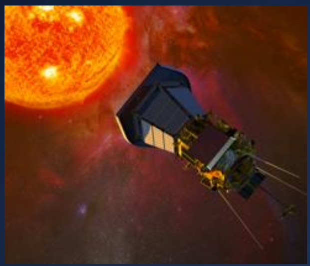
# CME-related SEP event near First Encounter



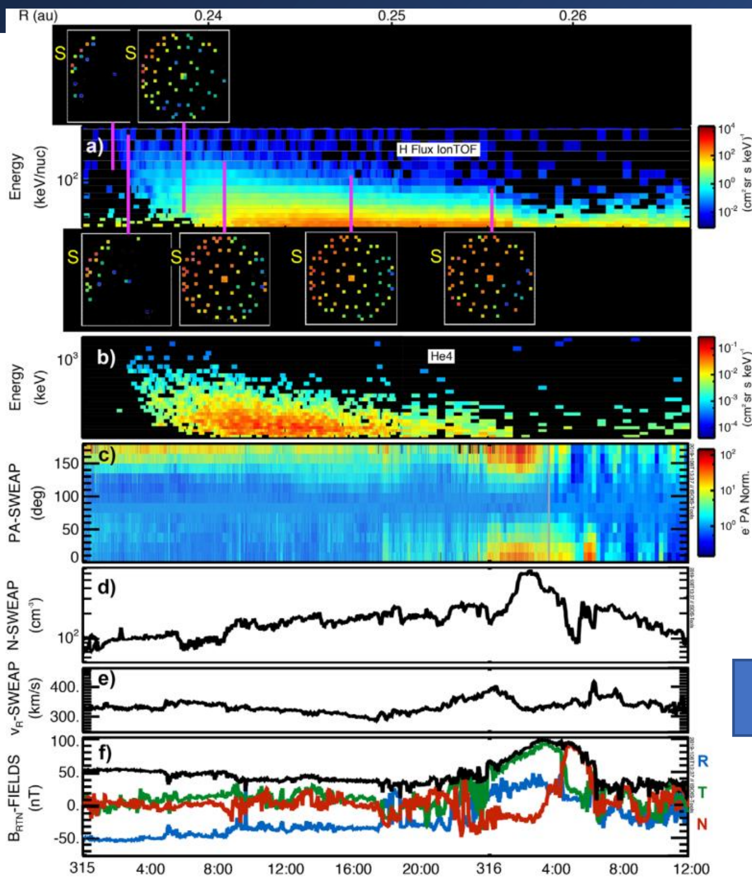



**Giacalone et al. 2020 *ApJS***

- SEP event is the result of particle acceleration at a weak shock or **compression** driven briefly by the CME when it was close to the Sun, which later dissipated before arriving at PSP
- The earliest arriving high-energy ions arrived to PSP with pitch-angle scattering in the turbulent IMF. Lower energy ions arrived later because they were scattered in the IMF more effectively than the higher energy ions
- <u>**Unique event:**</u> It is the closest to the Sun in which a CME-related SEP event was observed

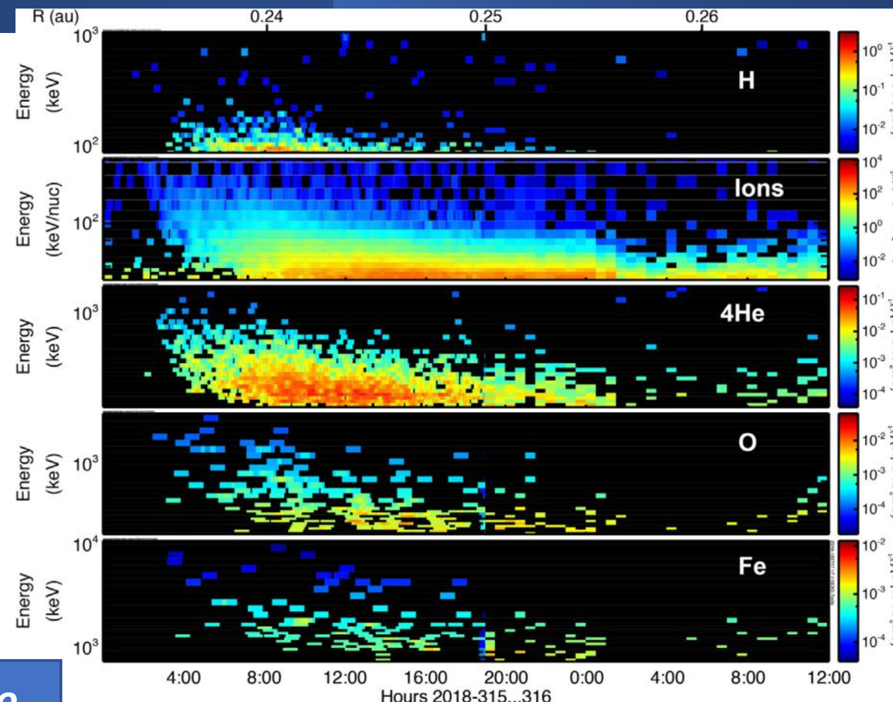


# CME-related SEP event near First Encounter Alternative interpretation: Auroral Pressure Cooker Mechanism




High anisotropy and VDA indicates a source near the Sun suggesting the ions had ready access to topologically open magnetic field connected to PSP at the time of their energization, when the CME was still relatively close to the Sun – below ~3-4 Rs (Giacalone et al. 2020)

EPI-Lo



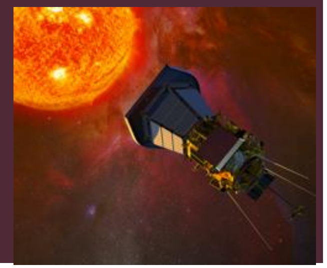

- ❖ Ion composition and peak energies reached:
  - **Protons** up to ~400 keV
  - **4He** to ~1MeV
  - **O** to ~2-3 MeV
  - **Fe** to ~8 MeV

Observations consistent with a process that involves charge dependence energization

**Mitchell et al. 2020 *ApJS***

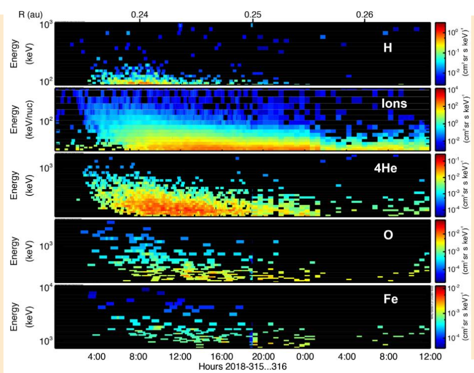
# CME-related SEP event near First Encounter

# Alternative interpretation: Auroral Pressure Cooker Mechanism



<u>'Pressure Cooker' Auroral process:</u>

- Field-Aligned Currents **(FACs)** drive the development of FA potentials in the Ionosphere-to-Magnetosphere transition. Plasma e⁻ accelerated to maintain the current so that charge neutrality of the plasma is not violated
- Anisotropic e⁻ drive instabilities resulting in the growth of broadband extremely low frequency (BBELF) waves perp. to B → interact efficiently with the plasma ions by ion cyclotron resonance with the various species (e.g. Japers 1998; Lynch et al. 2002), heating them in the direction perp. to B

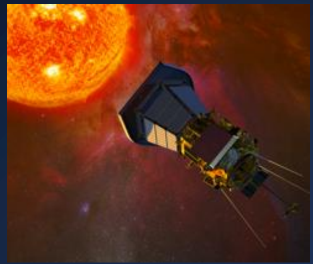



**In ↓ electric current regions**, the heated ions are confined by the potential and remain trapped in the wave field generated by the e⁻, gaining more E. Ions gain sufficient E perp. to B

→ mirror force becomes > enough to push the ions through the confining Ɛ force and escape upward as ion conics, which at large altitudes seen to be streaming close to field-aligned

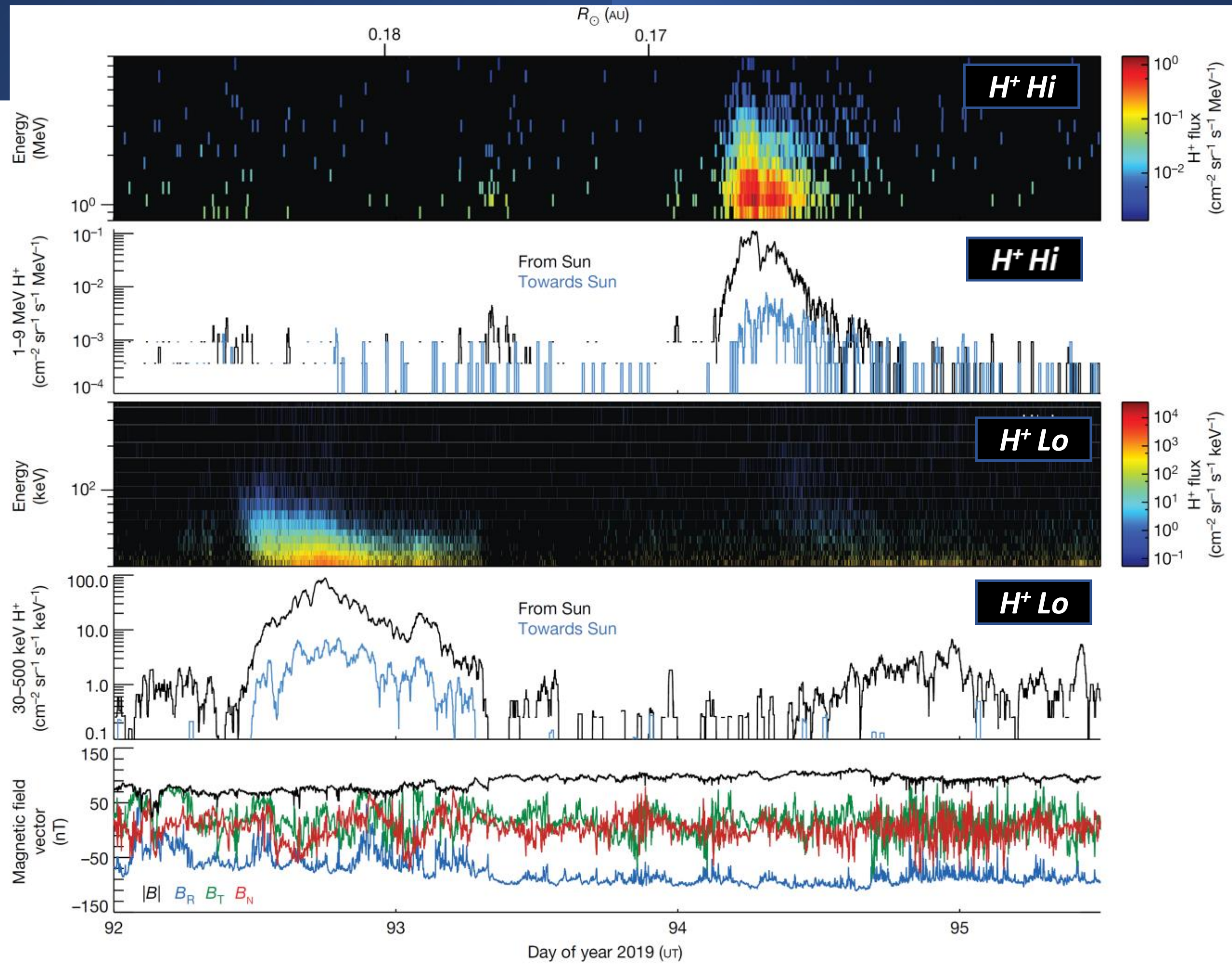
- 3 reasons for FACs to be enhanced in association with CME ejection e.g. **Kasper et al. 2019**: corotation of the coronal/sw plasma to **40 Rs**, much father from the Sun, than pre-PSP modeling predicted
- The torques required to keep the radially transported plasma, (sub)-corotating are transmitted by FACs from the footpoints of the B (ionosphere for Jupiter/Saturn or photosphere for the Sun) to the rotating plasma
- Ejection of a CME would involve increase in the mass of the plasma & the speed → enhancements in the corotation enforcement FACs associated with the transfer of angular momentum into the radially accelerating sw
- **Charge state dependence**: a natural consequence of this scenario, consistent with observed E ion dependence
- <u>Pressure Cooker mechanism:</u> attractive candidate for at least some of the SEP events produced during CME lift-off (Temerin and Roth, 1992 enhanced)
- Neither e⁻ nor tIII bursts observed

**Mitchell et al. 2020 *ApJS***



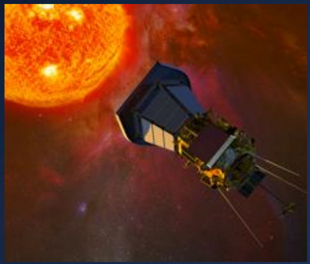
# SEP events observed during Second Encounter

- Very near Perihelion 2 (~35 Rs) ISOIS observed a unique pair of SEP events, the 1st one (2019-092) low-energy highly dispersive and the 2nd (2019-094) mostly at >1 MeV ions
- PSP is nearly corotational with the Sun near perihelion so the 2 events are magnetically connected to a common solar source
- Both events exhibit strong, persistent magnetic-field-aligned ions streaming away from the Sun



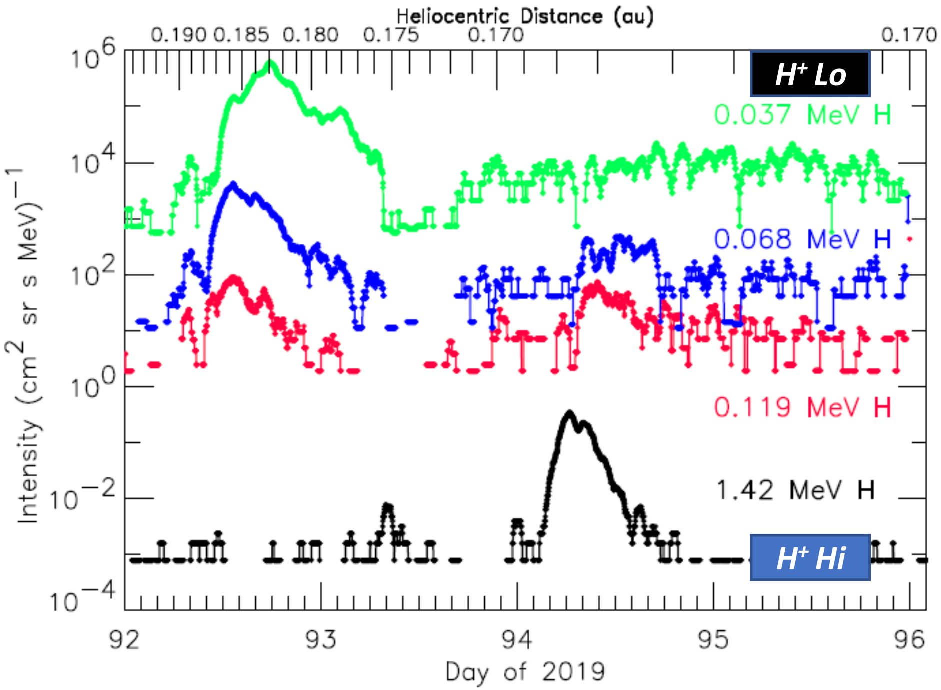

**McComas,…,Malandraki et al. 2019, *Nature***

- FIELDS data indicates possible lower β magnetic structure between the two events
- First SEP event: a classic Z-rich event (Roelof et al. 2020)

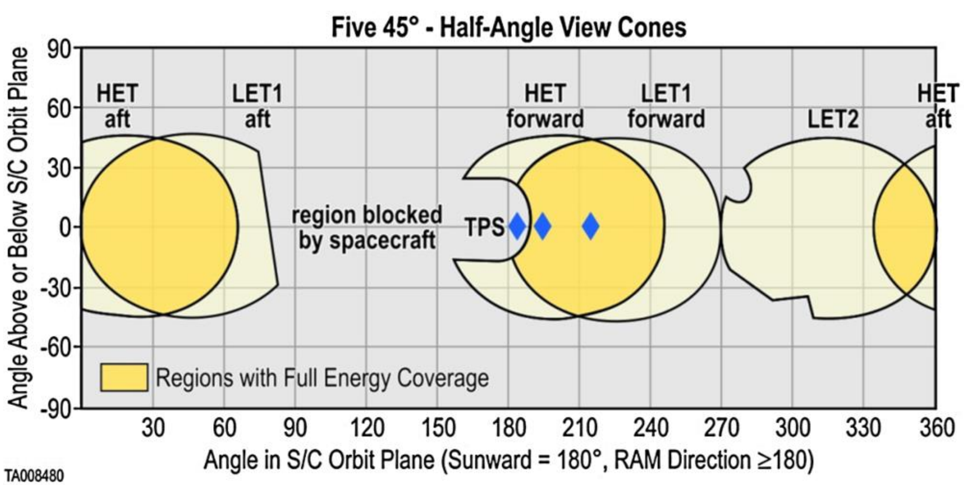


# 2019 April 4 SEP event during PSP Second Encounter

- Time profiles of proton intensities for the period 2019 Apr 2 00:00 – Apr 6 02:00
  Top three traces: **ISΘIS/EPI-Lo** TOF measur.
  Bottom trace: **ISΘIS/EPI-Hi/LET1** data
- Second event, PSP @ < 0.17 AU
- Increase in MeV protons obvious but much smaller in <100 keV particles and near bkdg levels. April 4 significantly harder proton energy spectrum than the April 2 event

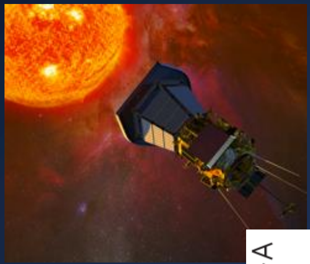



**Leske,…,Malandraki et al. 2020, *ApJS***

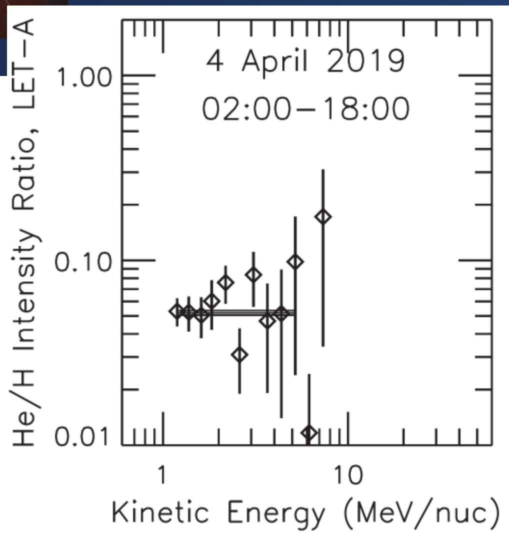


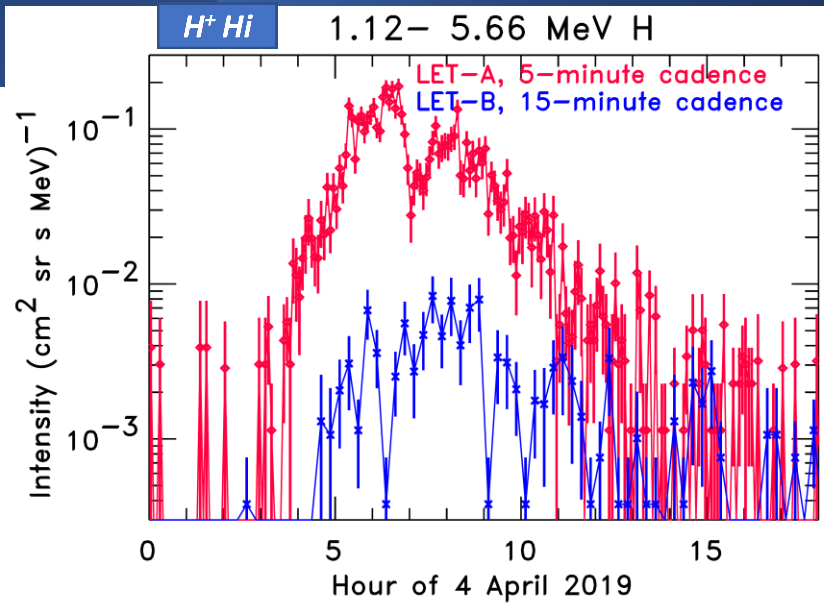

**McComas et al. 2016, *SSR***

During solar encounters one LET1 aperture (LET-A) is pointed 45$^o$ west of the Sun-s/c line, i.e. along the nominal Parker spiral direction at 1 AU, while the opposite end (LET-B) is pointed 135$^o$ east of the Sun. Due to favorable pointing directions, all EPI-Hi data used come exclusively from LET1, both A and B apertures



# 2019 April 4 SEP event during PSP Second Encounter



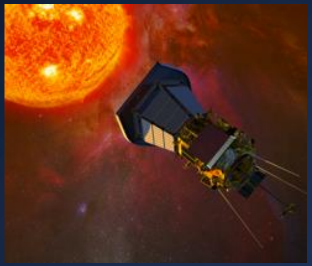



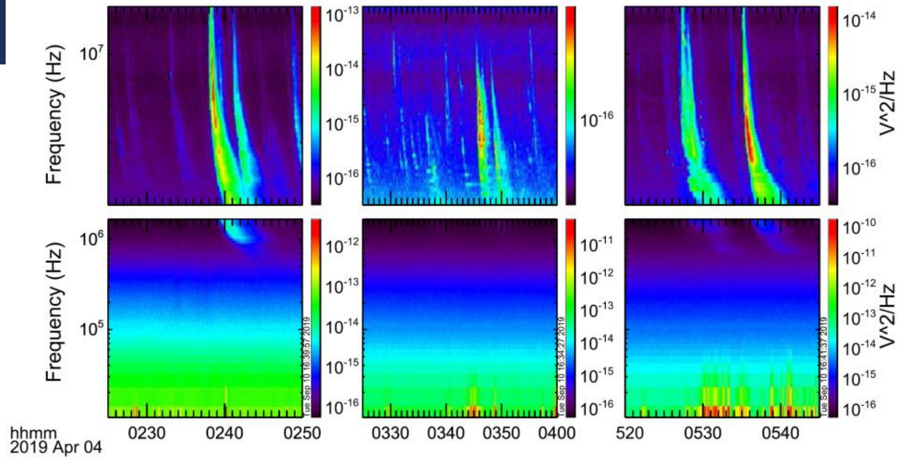

- Following bkgd subtraction, He/H ratio=0.052 ± 0.002, well-determined at 1-2 MeV/nucl, higher than typical value found in SEPs (Reames 2014). Ratio matches that of 0.052 ± 0.005 measured spectroscopically in the corona (Laming & Feldman 2001)
  - No $^{3}$He nuclei were detected in this very small SEP event
- No electrons or ions heavier than $^{4}$He were detected → *event is depleted in heavy elements compared with average SEP elemental composition*

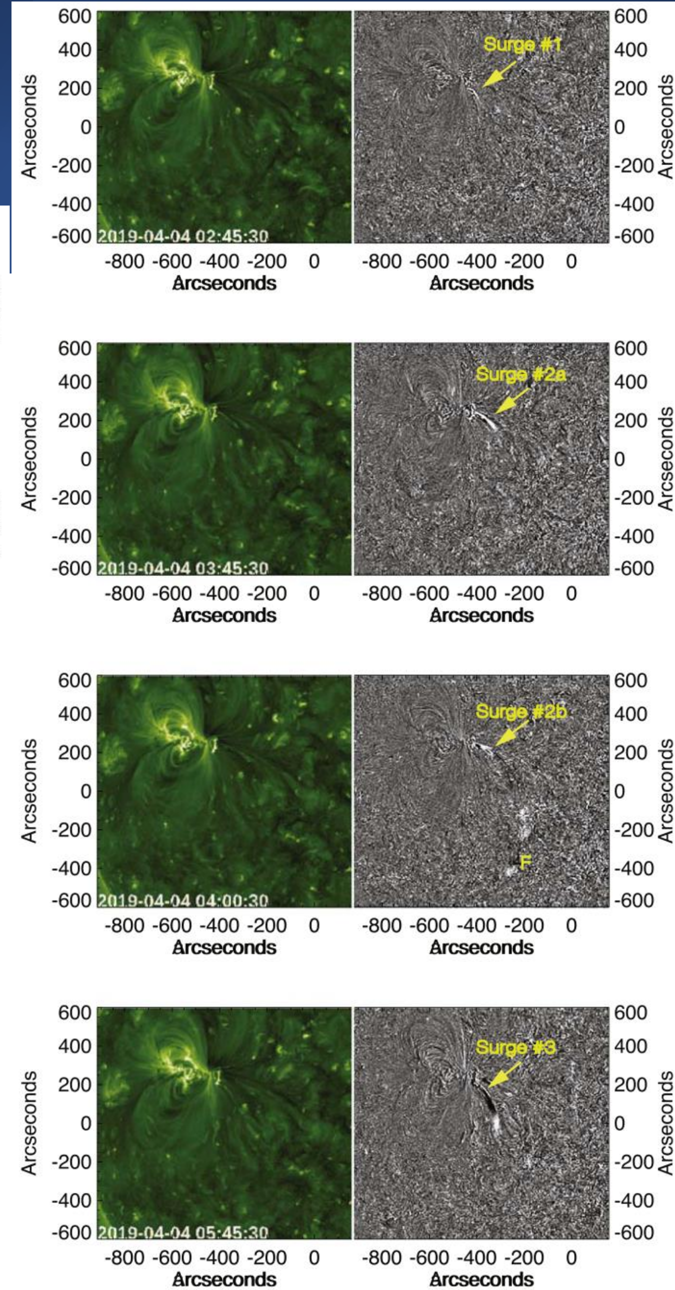
Time-profiles of 1.12-5.66 MeV protons on both LET-A and LET-B. Event very brief lasting ~ 15hr. ~4 hr from onset to reach peak intensities. SEP event highly anisotropic. Near peak, LET-A intensities a factor of ~30 greater than those in LET-B. SEP event had a soft power law index of -4.3

**Leske,…,Malandraki et al. 2020, *ApJS***

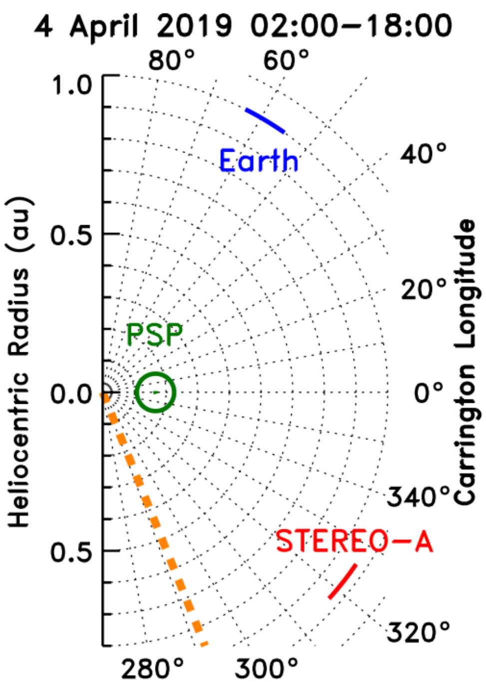
# 2019 April 4 SEP event during PSP Second Encounter





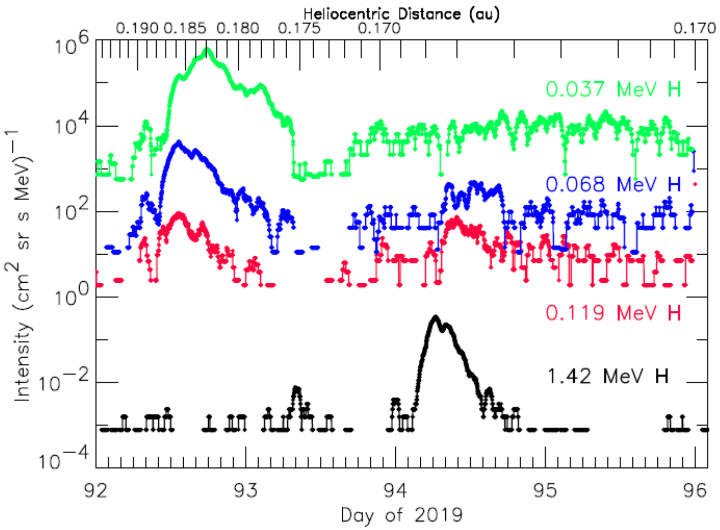



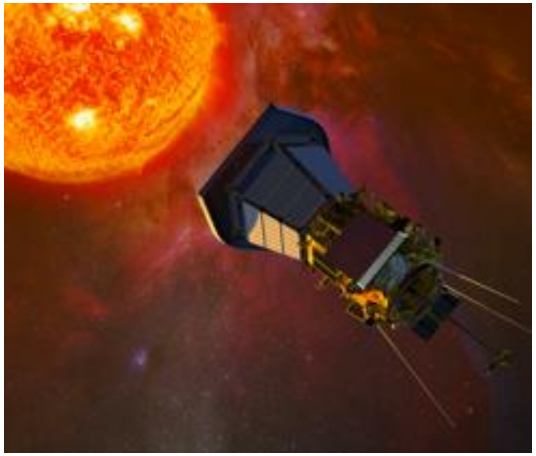

Locations of Earth, ST-A and PSP on April 4.




- STA and PSP only 35$^{o}$ apart in longitude and 1$^{o}$ apart in latitude
- STEREO/EUVI images show small Hα surges in the AR12738 (orange) ~80$^{o}$ east of the nominal magnetic footpoint, temporally associated with tIII emission detected by the FIELDS/RFS as well as the EPI-Hi energetic particles

Leske,…,Malandraki et al. 2020, *ApJS*



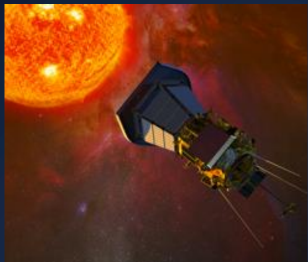





# 2019 April 4 SEP event during PSP Second Encounter

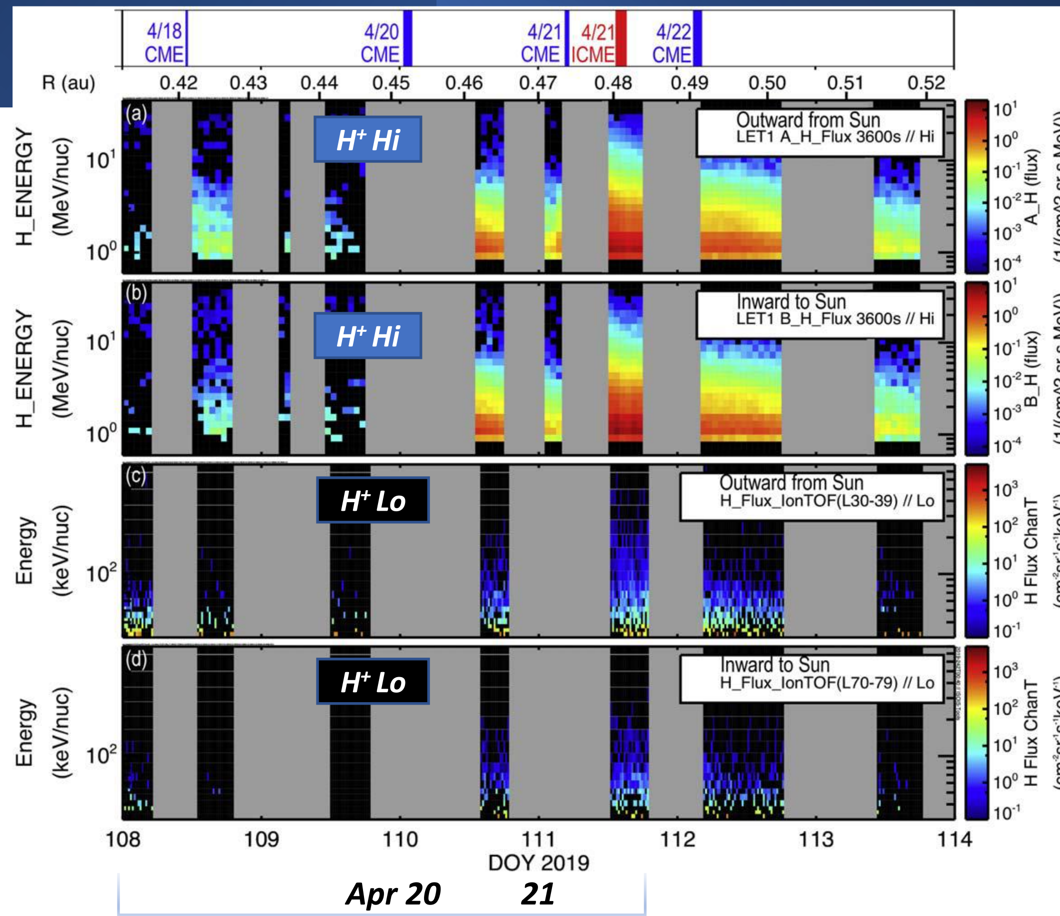
The very existence of this event, during an exceptionally quiet solar minimum and completely undetectable in situ at 1 AU, raises the possibility that such events are more common than one might expect, possibly providing an important source of seed particles available for acceleration in larger SEP events

**Leske,…,Malandraki et al. 2020, *ApJS***



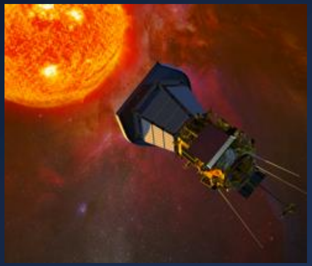
# Seed populations in April 19 SEP Event Second Encounter

- The same AR 12738 that was the source of the April 4 event produced the events in 2019 April 20-21, PSP @0.48 AU. The largest SEP events observed during the First two orbits of PSP
- EPI-Hi & EPI-Lo energetic particle fluxes from 2019 April 18 (108) to 24 (DOY 114).
- PSP instruments were operational only intermittently during this period
- Panels (a) EPI-Hi and (c) EPI-Lo: Fluxes **Outward** from the Sun along a nominal Parker spiral (V = 400 km/s)
- Panels (b) (EPI-Hi) and (d) EPI-Lo: Fluxes **Inward** from the Sun
- Early in the event observed distributions show larger anisotropies, which become increasingly isotropic after DOY 110.5

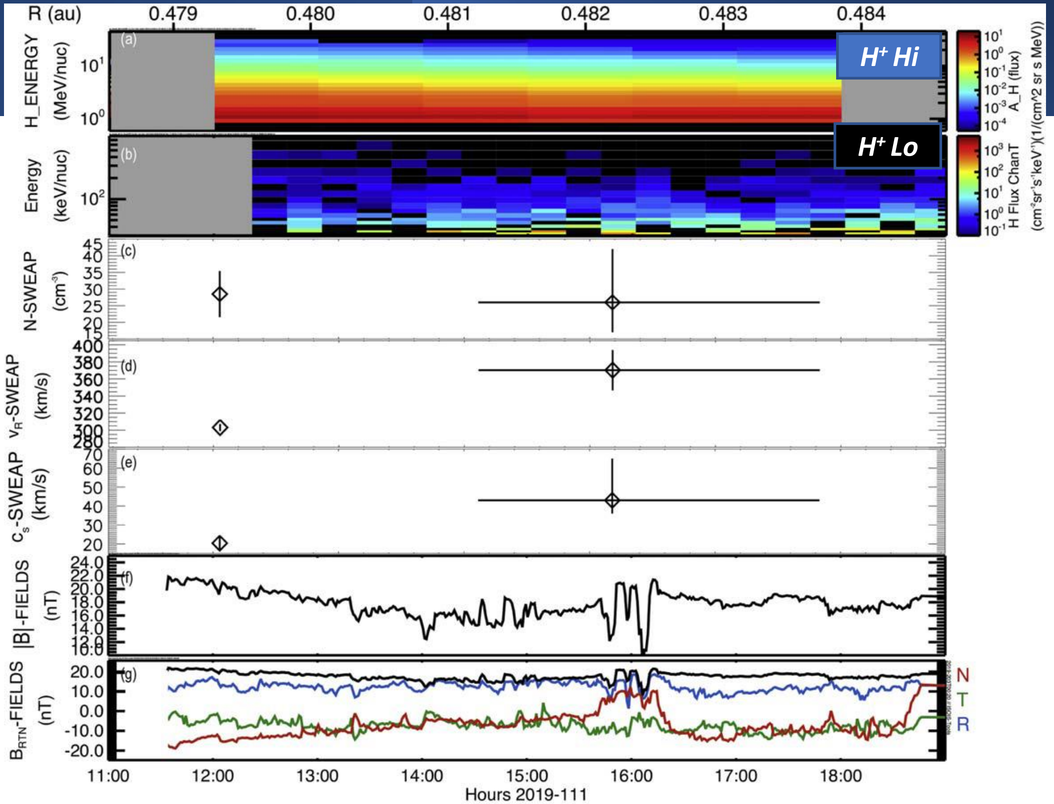



- CMEs released from the Sun on Apr 18, 20, 21 and 22. CME released on Apr 20 overtook PSP on April 21 ~16:00 UT

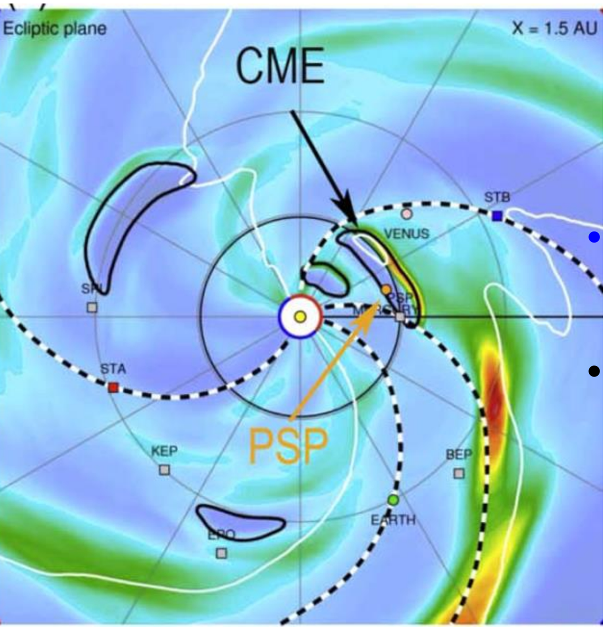
**Schwadron,…,Malandraki et al. 2020, *ApJS***



# Seed populations in April 19 SEP Event Second Encounter

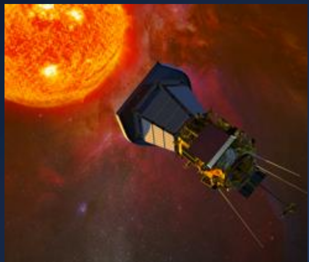



- Expanded view of the ICME passage over PSP. Panels a and b EPI-Hi and EPI-Lo (outward away from the Sun)
- **<u>A compressional plasma structure leading the ICME passing over the s/c</u>**: a gradient in the radial solar wind speed from V~300km/s to 380 km/s, along with a rise in the thermal speed

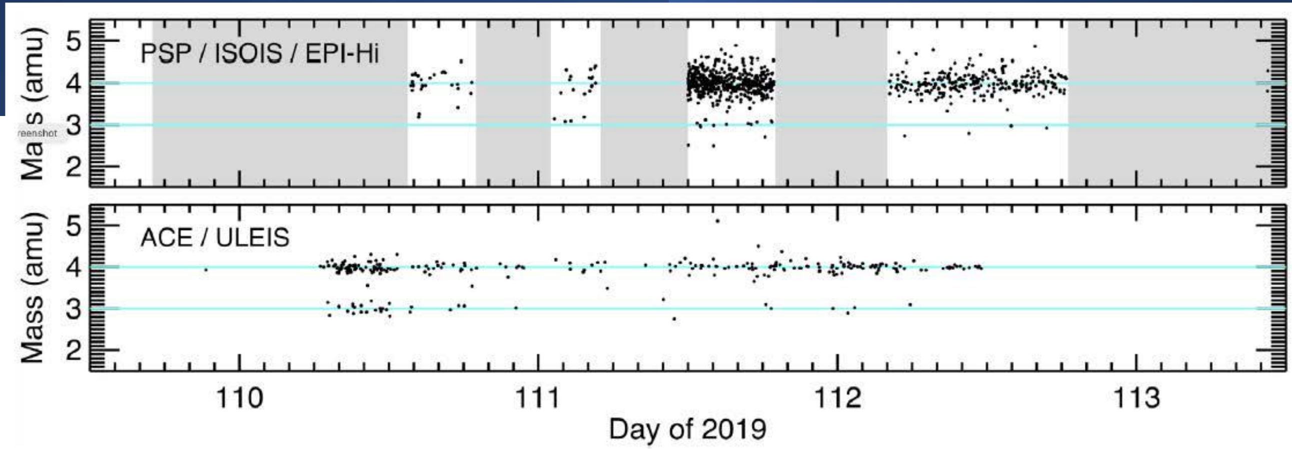



- **Br (blue curve)** and **|B| (black curve)** almost equal throughout April 21. A large **Br** throughout ICME ⇒ unlikely that a FR passed over PSP
- Modeling of the propagation of the CME released on Apr 20 from the Sun using the ENLIL model ⇒ the location of PSP is on the flank of the CME, consistent with plasma compression during the passage of the ICME without the accompanying signature of a Flux Rope

**Schwadron,…,Malandraki et al. 2020, *ApJS***

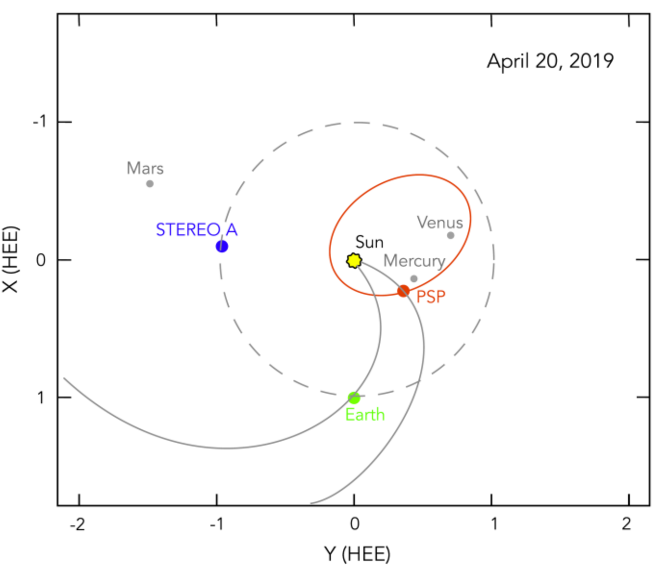


# Seed populations in April 19 SEP Event Second Encounter

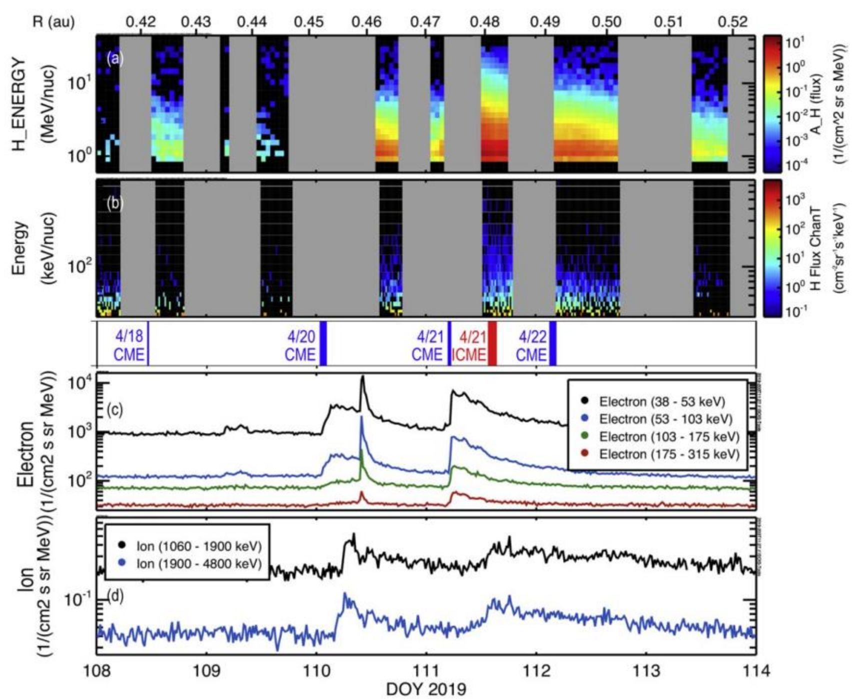



**Apr 20 & 21 events: strong $^{3}He$ enhancements observed by ISOIS**

**Wiedenbeck,…,Malandraki et al. 2020, *ApJS***




The period under study was unique since **PSP** was close to being magnetically connected to the s/c near **Earth!**

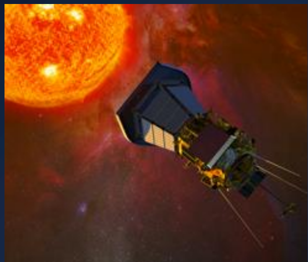



**ACE/EPAM**

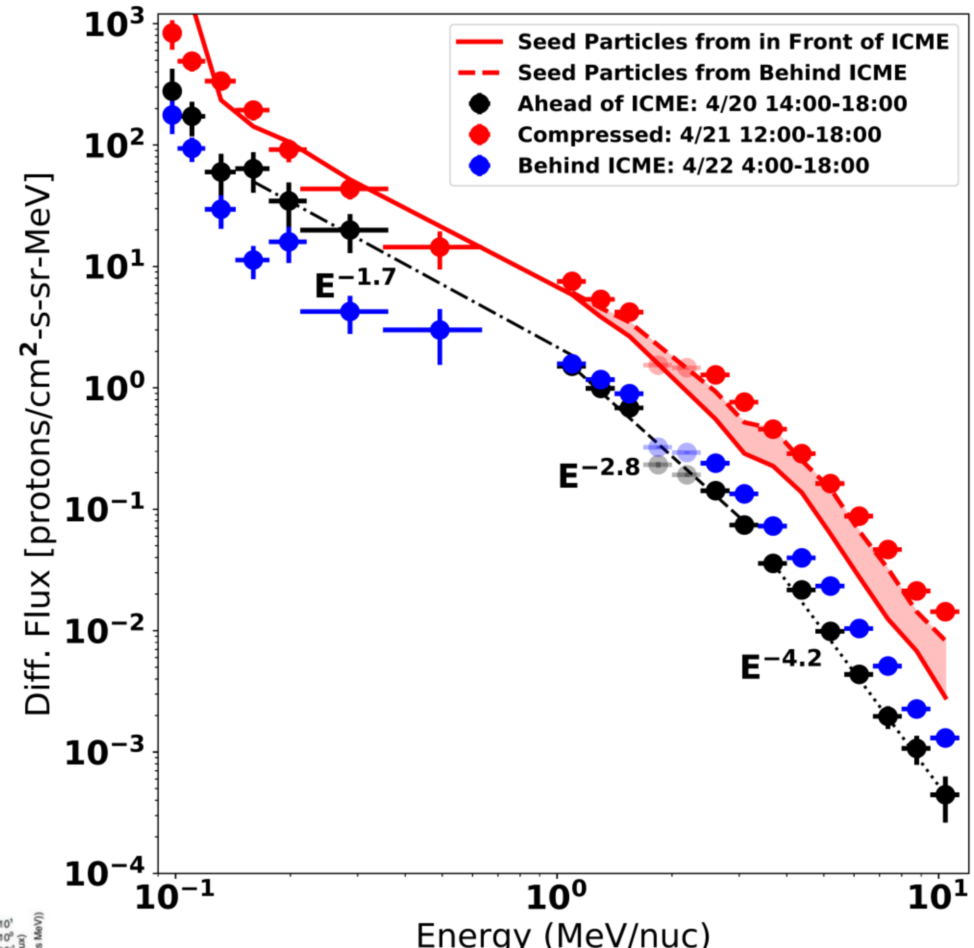
Apr 20 & 21: 2 NR prompt Electron events in which particles accelerated in a magnetically well-connected solar source region arrive abruptly @ the s/c (Malandraki et al. 2002)

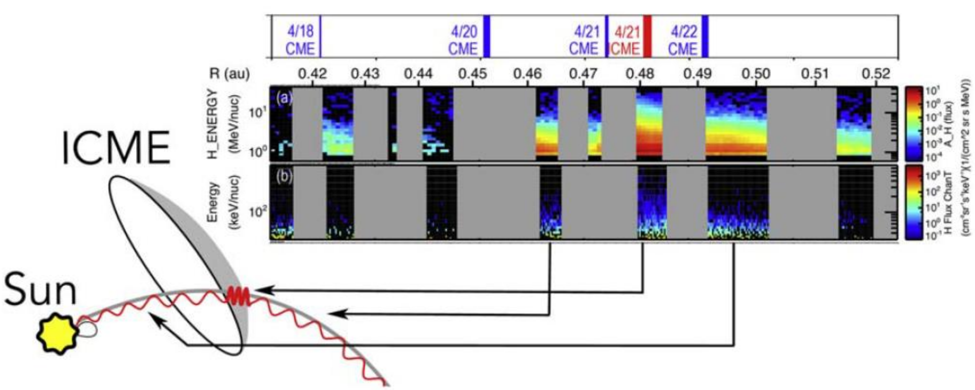
**Schwadron,…,Malandraki et al. 2020, *ApJS***

# Seed populations in April 19 SEP Event Second Encounter



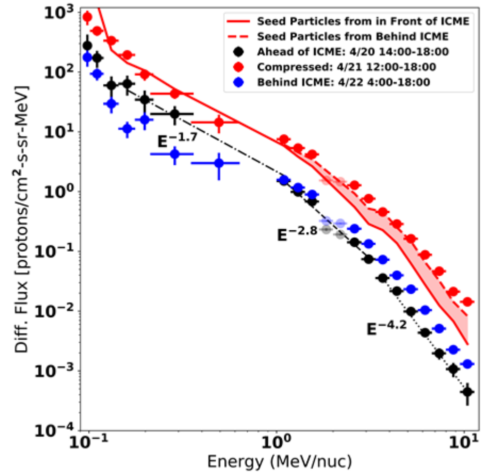
- ISOIS ion spectra averaged **before,** **during** and **after** the ICME passage. The spectra are very similar but the diff. energy spectrum **during** the ICME passage is almost uniformly enhanced relative to the diff. spectra observed **before,** and **after** the ICME passage
- With a reduced scattering mean free path of 0.006 AU in the ICME compression region, the DSA to 1 MeV would require >2.5 days ⇒ unlikely that the local enhancements observed in Apr 21 at PSP can be accounted by local DSA

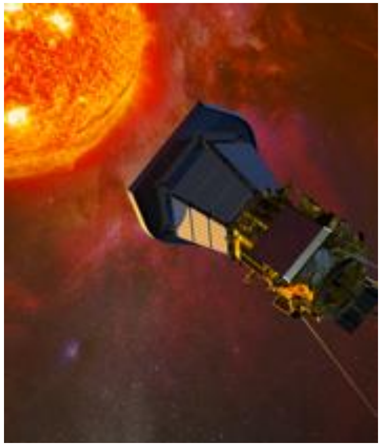



The **fluxes predicted (red curves)** by the compression mechanism are generally similar to observations within the ICME-driven compression

**Schwadron,…,Malandraki et al. 2020, *ApJS***



# Summary and Conclusions

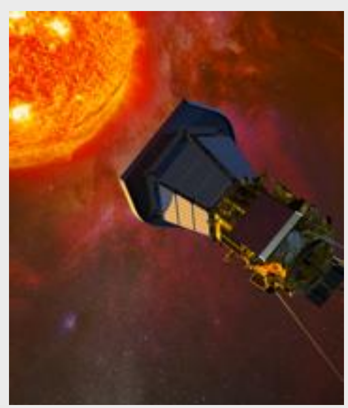
- Observation of a time period in 2019 Apr 21 in which the flank of ICME passed over PSP @0.48 AU. The solar wind plasma ahead of the ICME contained strong enhancements in EP fluxes that appear to have been compressed and accelerated within the sheath ahead of the CME
- Contemporaneous observation of strong $^3$He enhancements (Wiedenbeck et al. 2020) confirm that seed populations are rich in material released by solar flares. The presence of NR electron seed populations is demonstrated by the analysis of ACE/EPAM observations near Earth
- A broken power law > 1 MeV in the compressed ICME sheath consistent with predictions of diffusive shock acceleration from shocks (Li et al. 2009) or compressions from low in the corona (Schwadron et al. 2015)
- The ISOIS observations show a very hard $E^{-1.7}$ energy spectrum @ < 1 MeV. It is close to the $E^{-1.5}$ limit of possible stationary-state plasma distributions out of equilibrium (Livadiotis and McComas, 2009, 2010)

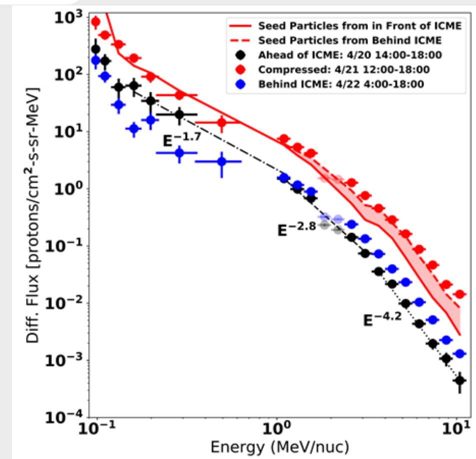


**Schwadron,…,Malandraki et al. 2020, *ApJS***

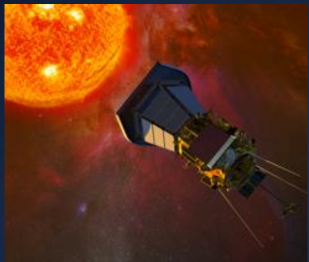
# Summary and Conclusions

PSP was at the right place and at the right time to observe the compression of energetic particle seed populations. The enhancements in EP seed populations observed demonstrate how the early evolution of ICMEs could enhance the fluxes of energetic particle seed populations, which precondition the particle acceleration process at distances farther from the Sun where compressions can steepen into shocks





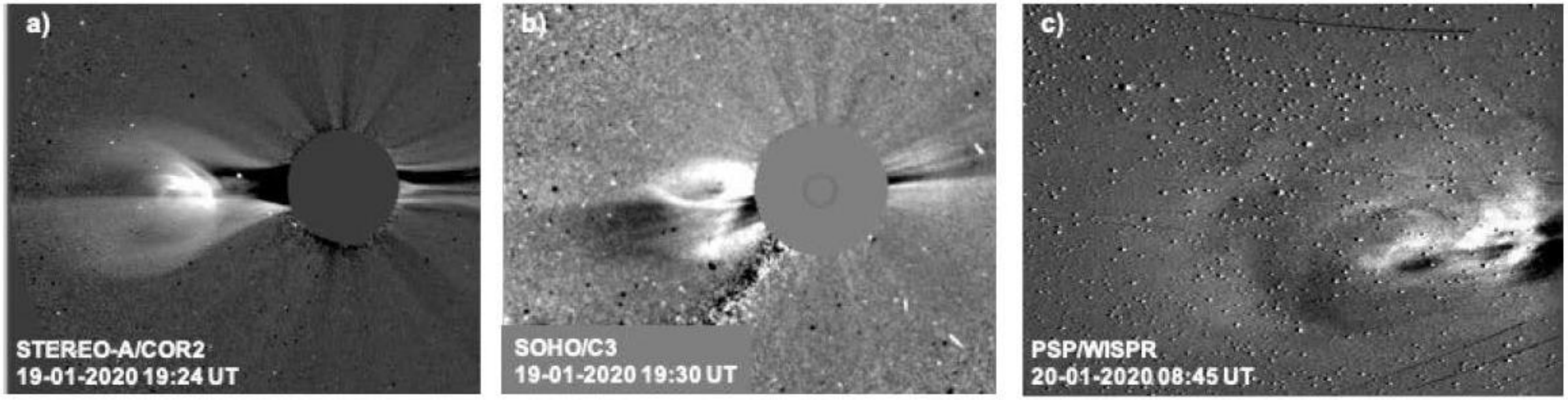

**Schwadron,…,Malandraki et al. 2020, *ApJS***



# *Orbit 4:* Energetic particle evolution during CME passage from ~0.3 to 1 AU

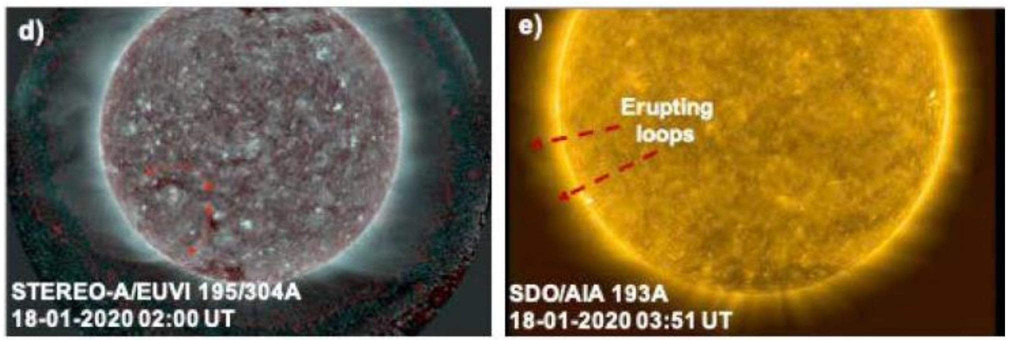
Joyce et al. 2021, *A&A*

Analysis of a CME observed by PSP/ISOIS at 0.32 AU

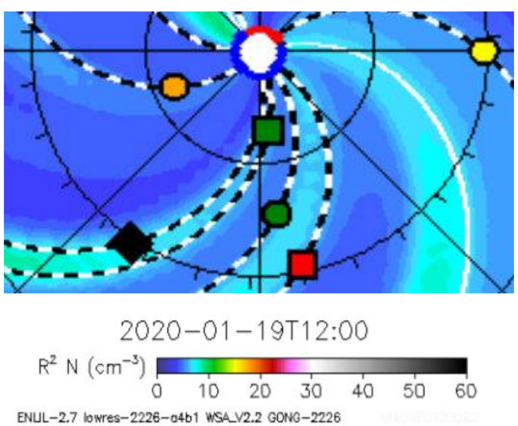



**CME was ejected from Sun on day 19 of 2020 and passed over PSP later on day 21**

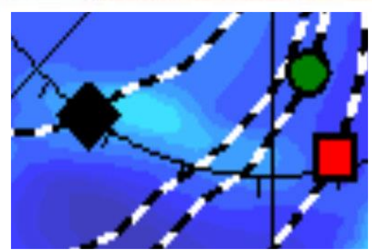
**CME propagation speed to PSP is ~400 km/s**




red arrows demarcate the source region in EUVI, based on the eruptive loops seen in SDO/AIA

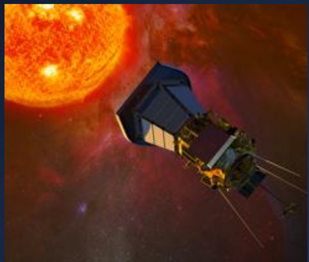



Time when CME was ejected from the Sun



Simulation results from WSA-ENLIL+Cone model (CCMC)

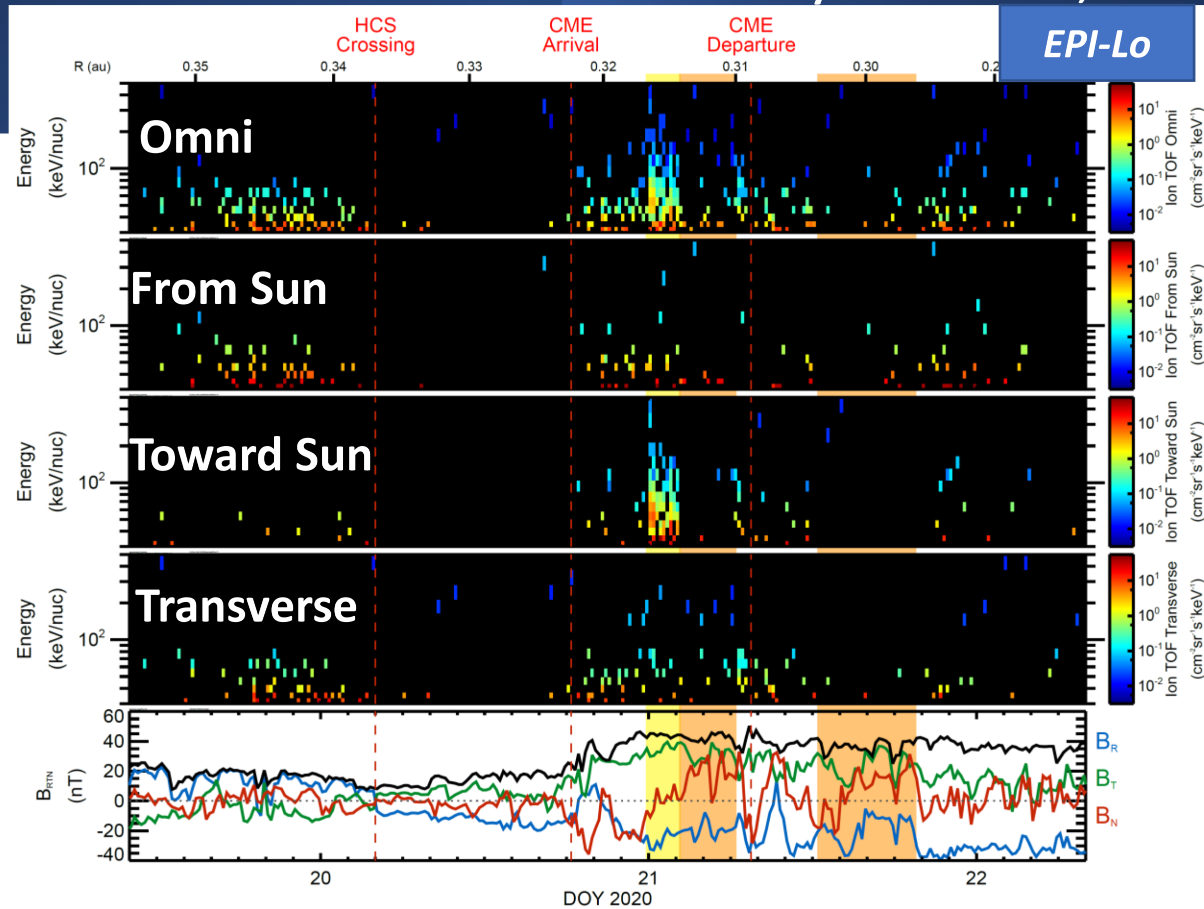
Enlarged images of the times CME was passing over **PSP** & **ST-A** to better show the CME position. **PSP** & **ST-A** radially well-aligned. Both encountered the CME near its western flank. Earth well-positioned for SOHO to observe CME ejection off the East limb



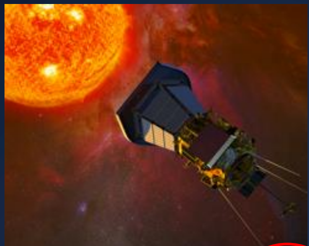
# *Orbit 4:* Energetic particle evolution during CME passage at 0.3 AU

Joyce et al. 2021, *A&A*

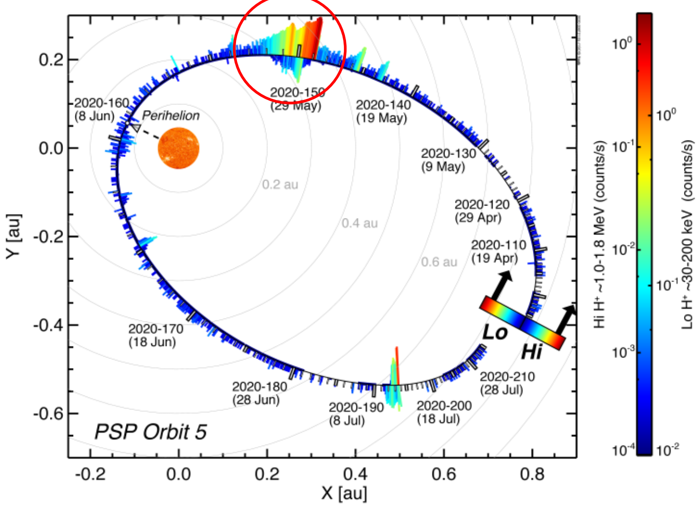
- Mid-way through Jan 19: EP largely seen coming from the Sun, with strong evidence of VD. However, at CME passage $B_N$ rotates which coincides with a strong influx of particles moving toward the Sun (yellow). A particle flux dropout observed. A near total EP dropout is also observed later
- The strong anisotropies and dispersive EP signatures consistent with a remote source and one close to the Sun (**CME**)
- **Extremely soft spectra** (**γ=-8**) prior to and following CME → may be a common feature in the previously unexplored near-Sun region



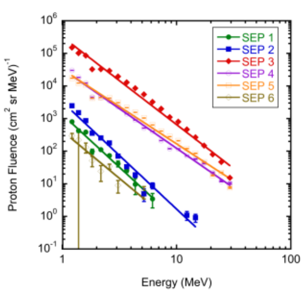

- **STA**: EP more uniform throughout the event in contrast to strong variations at PSP. Mixing of different EP populations as CME propagates outward from the Sun + transport effects acting on EP in transit. PSP data close to the Sun crucial!
  - **Unique case study:** How EP populations evolve as CMEs propagate through the heliosphere

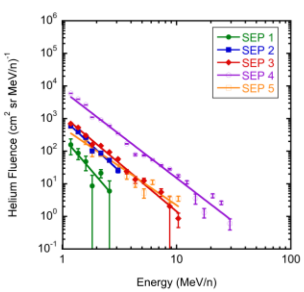


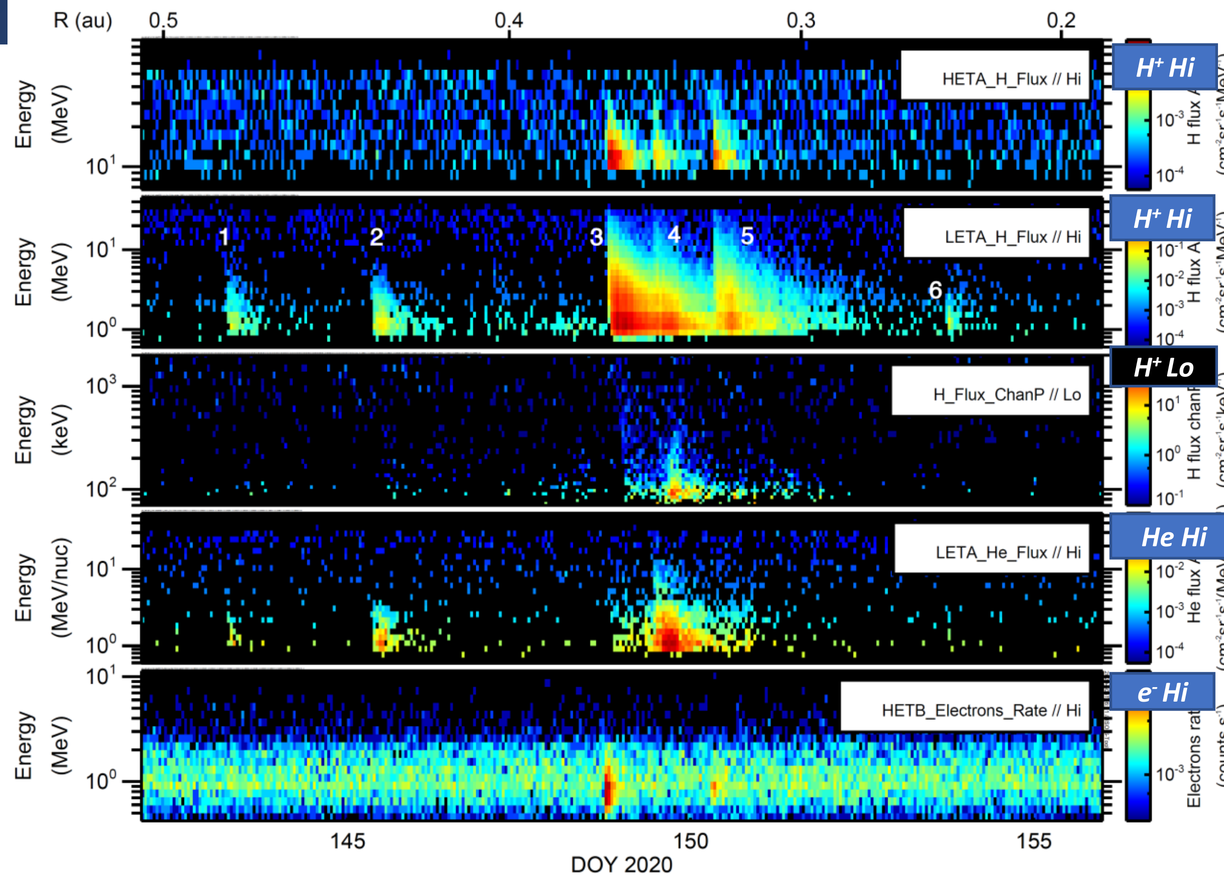
# *Orbit 5:* PSP observations of He/H Abundance Vatiations in SEP Events < 0.5 AU




- PSP observed a series of 6 SEP events in May-June 2020 during Orbit 5 just before perihelion, from **0.45-0.3 AU**
- All events well described by power laws with γ==2.3-3.3 (H)



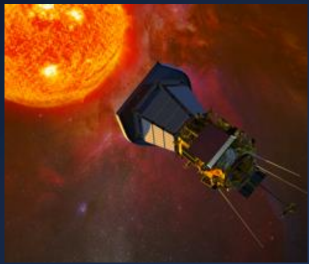




H, He, electron spectrographs for the 6 events

- clear in LET H
- less so in EPI-Lo H
- 3 extend >10 MeV
- Electrons are seen in 2 events
- Clear He variability

**Cohen et al. 2021, *A&A***

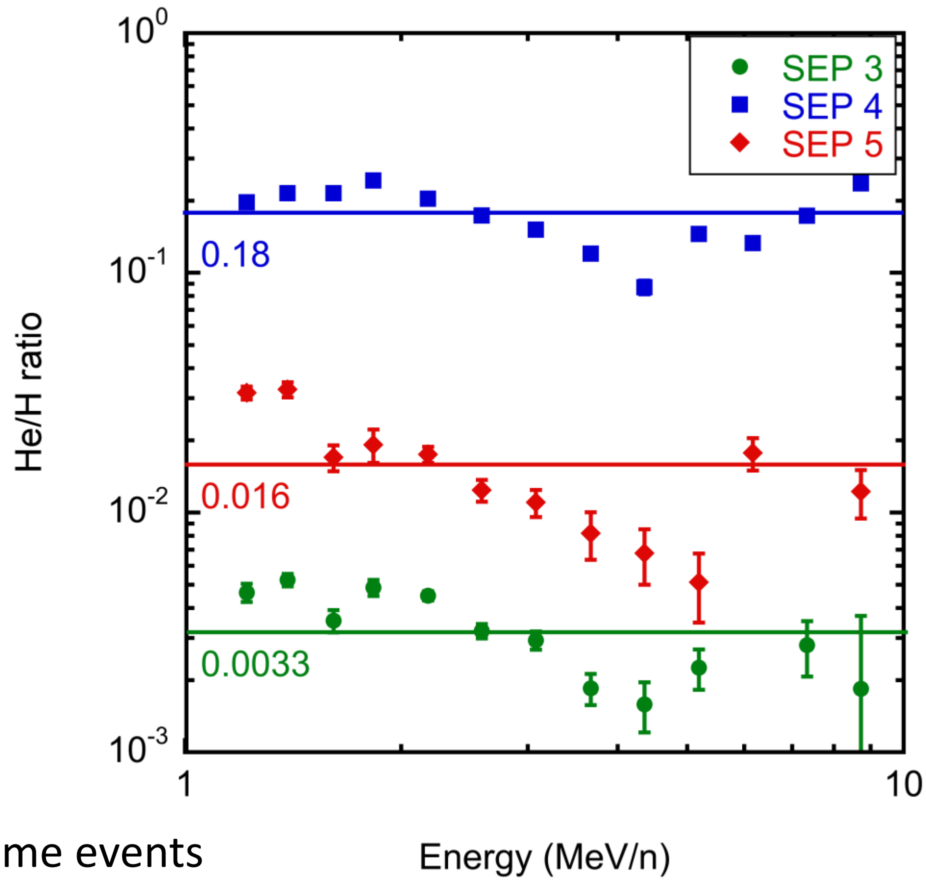


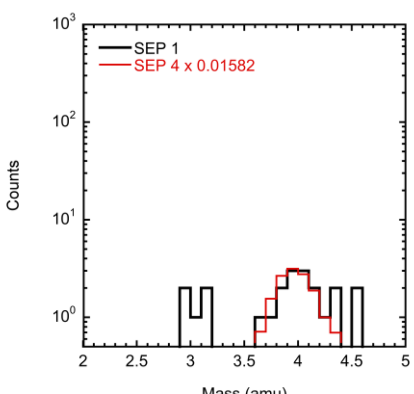
# *Orbit 5:* PSP observations of He/H Abundance Vatiations in SEP Events < 0.5 AU

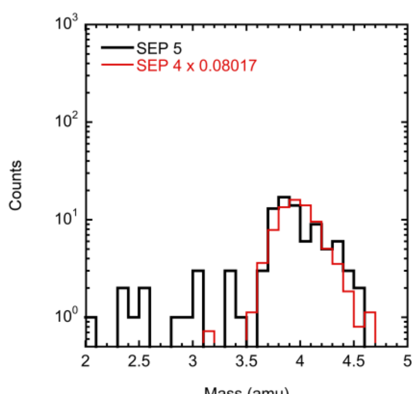
Cohen et al. 2021, *A&A*

## Composition

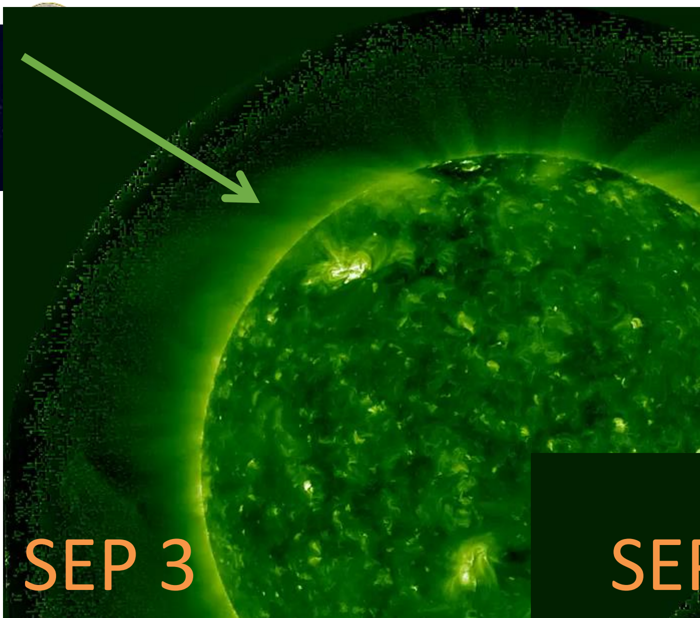
- He/H vs E for triad events (3-5)
  - Ratio is approximately independent of energy
  - Factor of >50 variation 0.003-0.18
- Variation is surprising given that
  - they are likely from the same source region
  - the associated eruption signatures are very similar

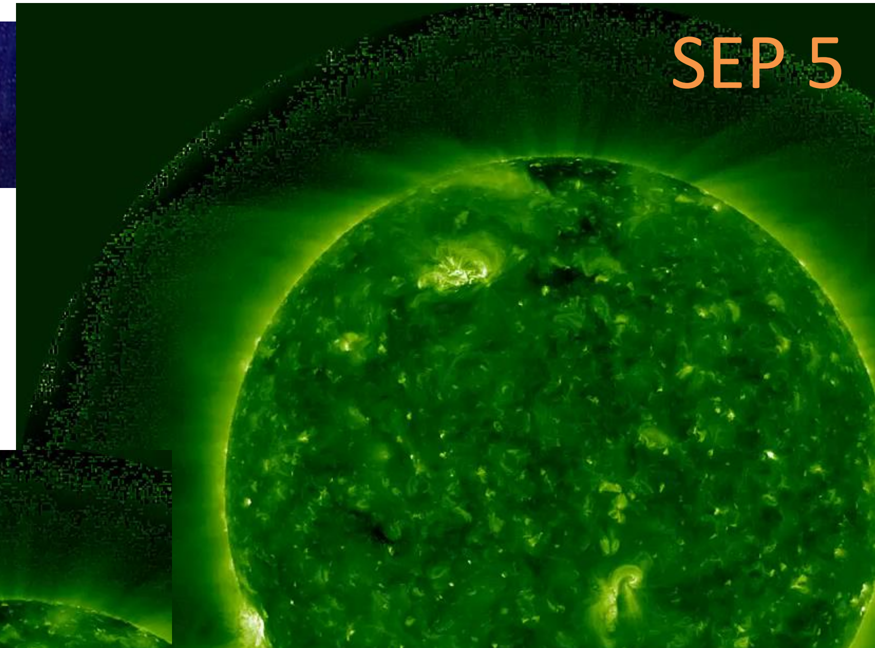


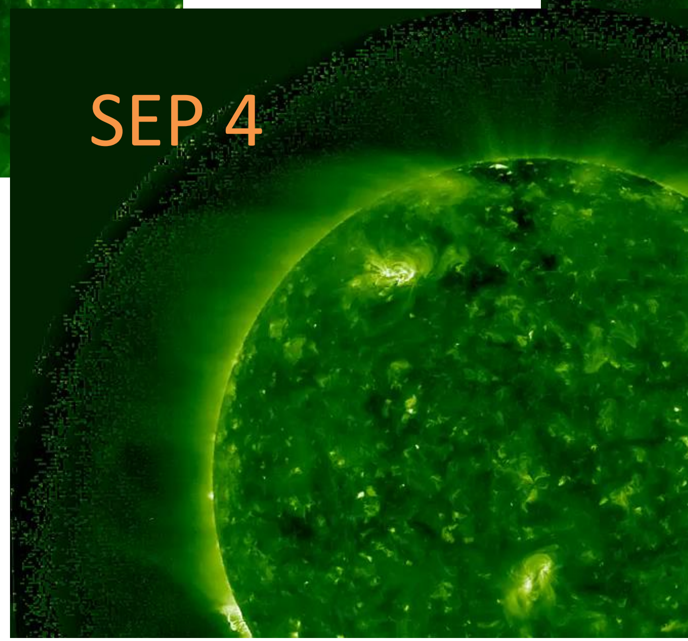




Some events have significant **$^3He/^4He$**



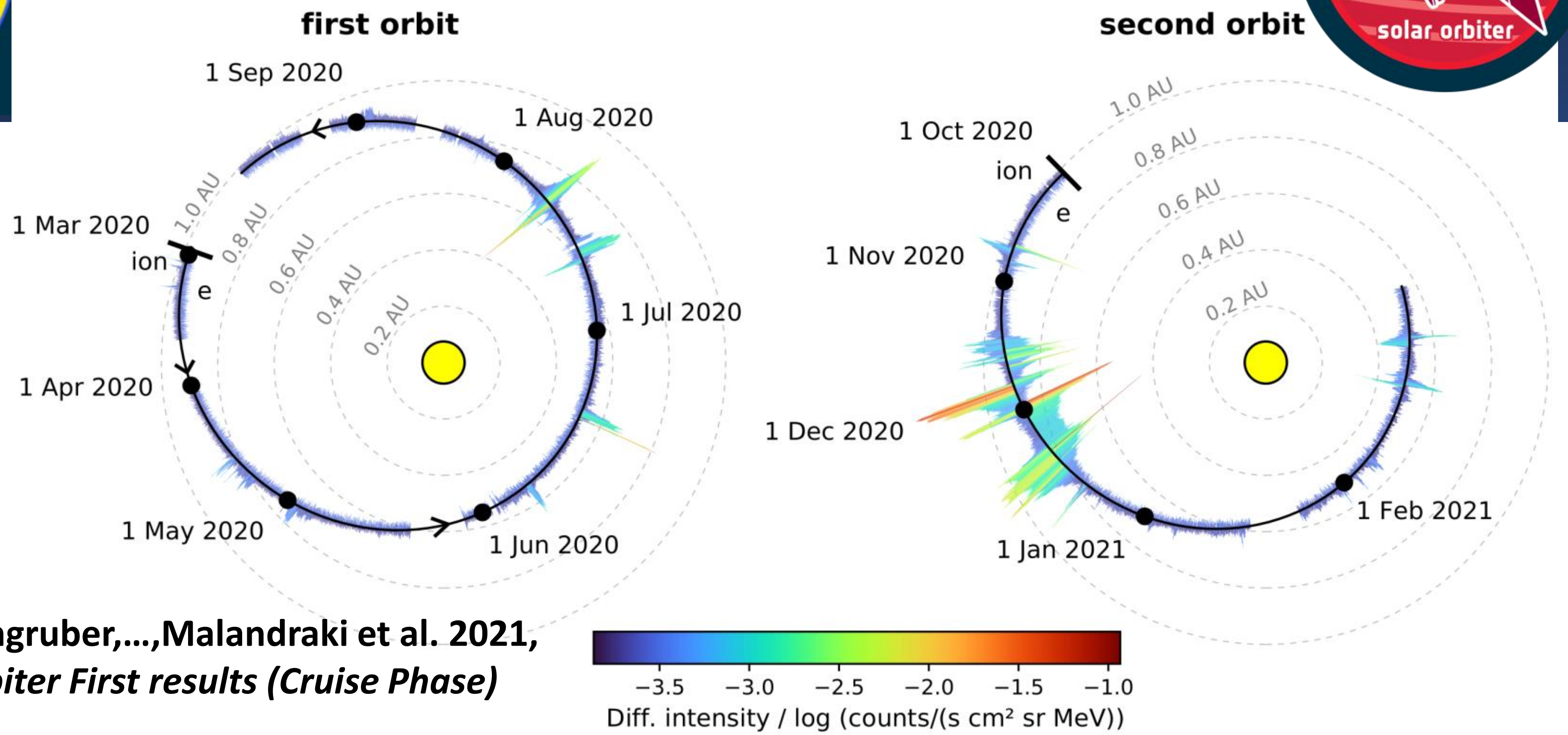




- **STEREO/EUVI** images of associated solar source : **EUV waves (AR 12764)** → implies particle acceleration may be occurring very low in the corona and early in the eruptive process

**Cohen et al. 2021, *A&A***

**Chhiber et al. 2021, *A&A:*** Long apparent pathlength during these SEP events can be explained by 1) a magnetic field line pathlength increase due to field line random walk, 2) particle transport about the guiding center with a non zero effective pitch angle

# First year of EP measurements in the inner heliosphere with SolO/EPD




**Wimmer-Schweingruber,…,Malandraki et al. 2021,**
***A&A, Solar Orbiter First results (Cruise Phase)***

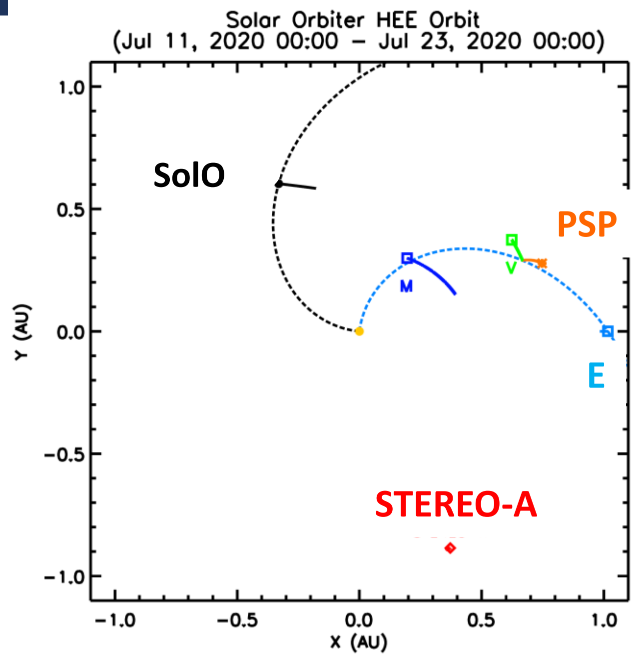
- SolO's trajectory for the First Year of measurements of EPD – **28 February 2020 - 28 February 2021**. 54-101 keV $e^-$ intensities on inner side, 124-218 keV $i^+$ on outer side as measured by EPT. Projection of the orbit onto the ecliptic shown
- Apart from a low-level bckgd activity (Mason et al. 2021) and small increases due to CIRs (Allen et al. 2020) a number of intensity increases or particle events observed
- First-year overview paper: provides updates on EPD, additional insights into its operation and data products based on EPD's 1st year of operation, guidance and examples for the usage of the EPD data. Also, a list of the most significant particle enhancements (EPT) during its 1st year of operation

# First near-relativistic solar electron events observed by SolO/EPD

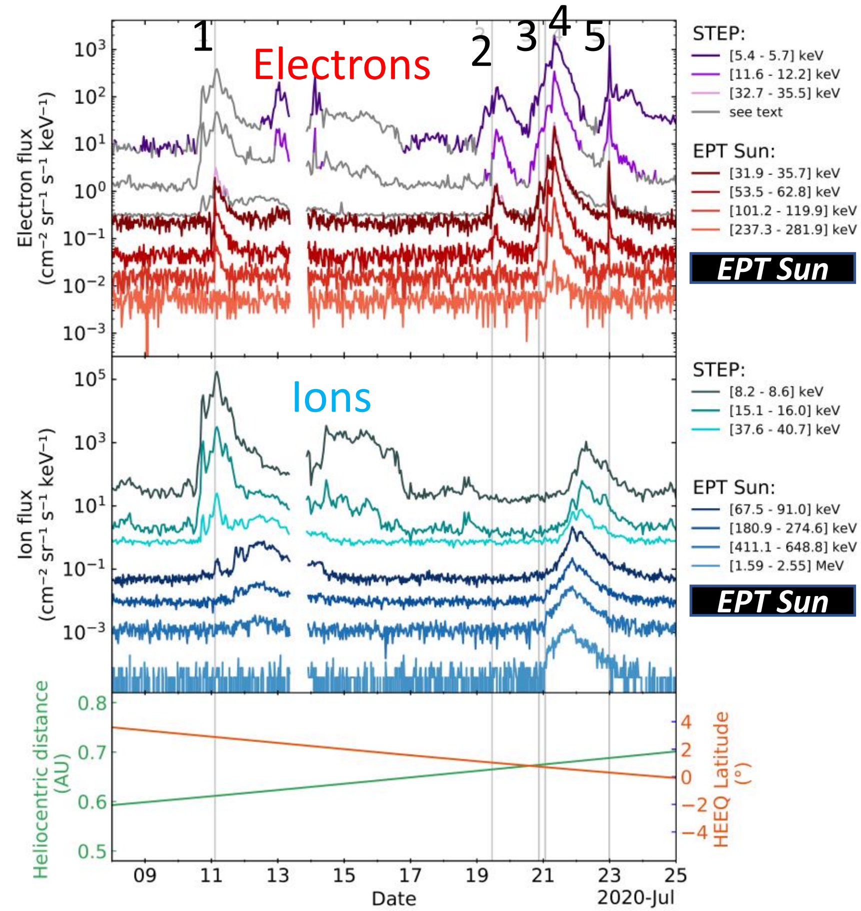
Gómez-Herrero,…,Malandraki et al. 2021

*Solar Orbiter First results (Cruise Phase)*

- SolO/EPD observed 5 NR e⁻ increases in July 2020
- Combine EPD e⁻ observations (keV to NR range) with tIII radio bursts from RPW (Maksimovic et al. 2020) and EUV obs. from **ST-A** and the near-Earth **SDO** to identify the solar origin of the in-situ NR e⁻ events




Trajectories of SolO, the inner planets, ST-A, and PSP from 2020 July, 11-23 (ecliptic plane projection, HEE frame). Nominal Parker spirals for a 300 km/s for July 23. SolO magnetically connected to the solar backside (as viewed from Earth)

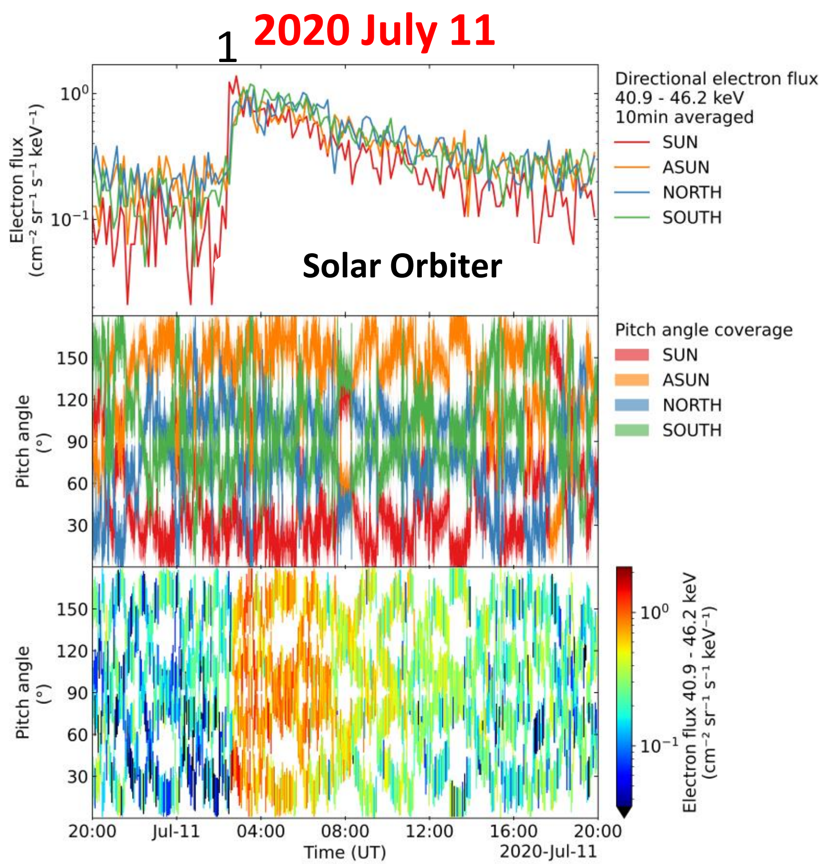


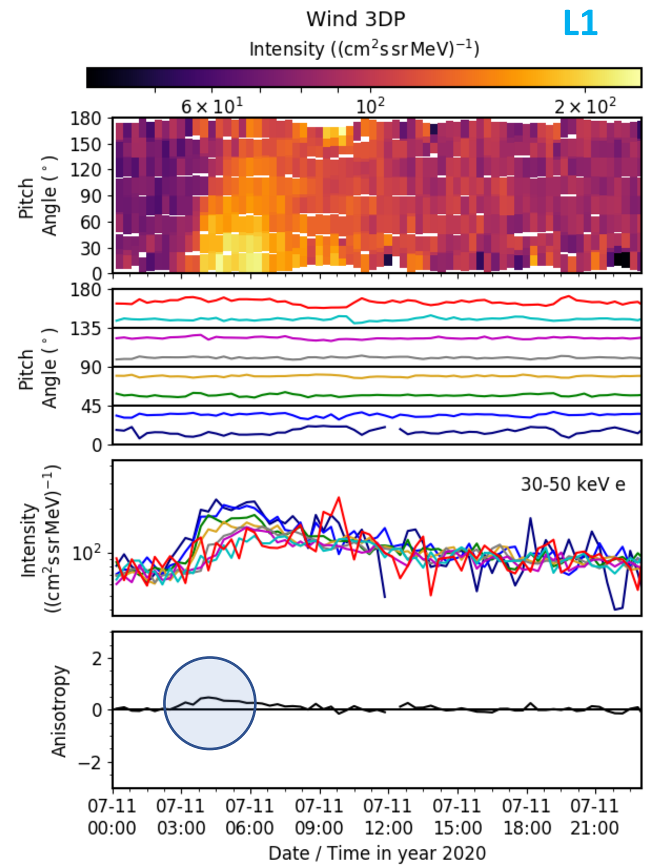

Electr. and ion intensity time profiles by the SW-looking EPD/EPT telescope and the 15-pixel-averaged e⁻ and i⁺ intensity time profiles by EPD/STEP for Jul 8-25, 2020

# First near-relativistic solar electron events observed by SolO/EPD

Gómez-Herrero,…,Malandraki et al. 2021, *A&A*

- 1) 40.9-46.2 keV e⁻ intensities by the 4 EPD apertures
- 2) PA coverage of each aperture
- 3) PAD color-coded intensity for e⁻ shown on top
- 58 keV e⁻ flux rises at 02:33 UT±5 min
- Vel. Disp. in the energy range covered by EPT but no significant increase >170 keV



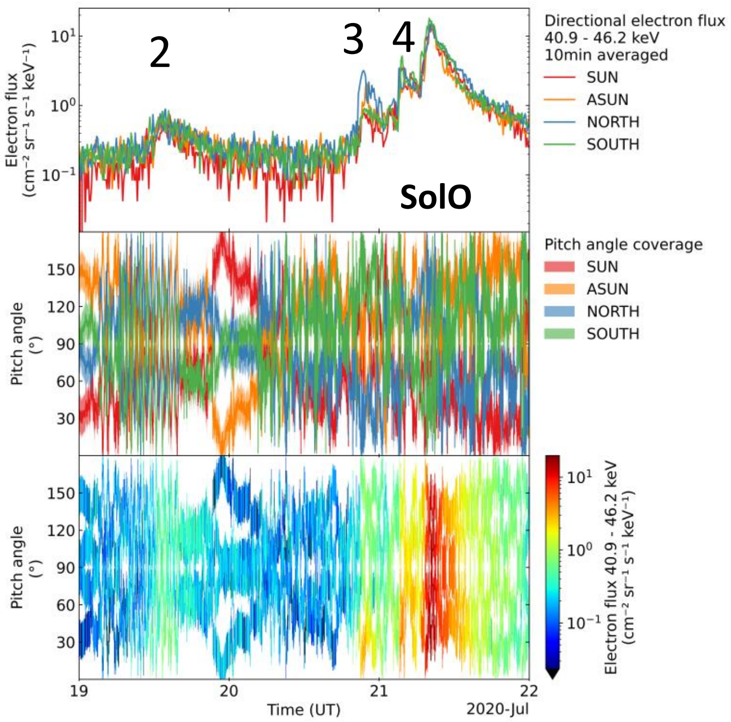

- Event observed by all EPT telescopes; however, a moderate anisotropy present during rising phase, with higher fluxes observed by EPT-Sun aperture, pointing SW along nominal Parker spiral direction
- Event also observed near Earth by Wind/3DP located 107 eastward from SolO. In spite of the significant difference in connectivity, Wind/3DP also observed moderate anisotropies

# First near-relativistic solar electron events observed by SolO/EPD

Gómez-Herrero,…,Malandraki et al. 2021, *A&A*

- **Jul 19**: 58 keV e$^-$ flux showed a gradual rise @ 11:00 ± 1h. Not visible > 70 keV. No significant anisotropies nor VD
- **Jul 20**: 58 keV e$^-$ flux started to rise @20:40 UT ± 10min. The highest intensity and earliest onset were observed by the Northward-looking EPT telescope, pointing closer to pitch angle 0$^o$
- **Jul 21**: Event comprises at least 3 consecutive, partly overlapping e$^-$ injections with onsets at 01:25, 03:05, and 06:25 UT ± 10 min (@ 58 keV). EPT directional intensities revealed measurable anisotropies but smaller than during the previous event

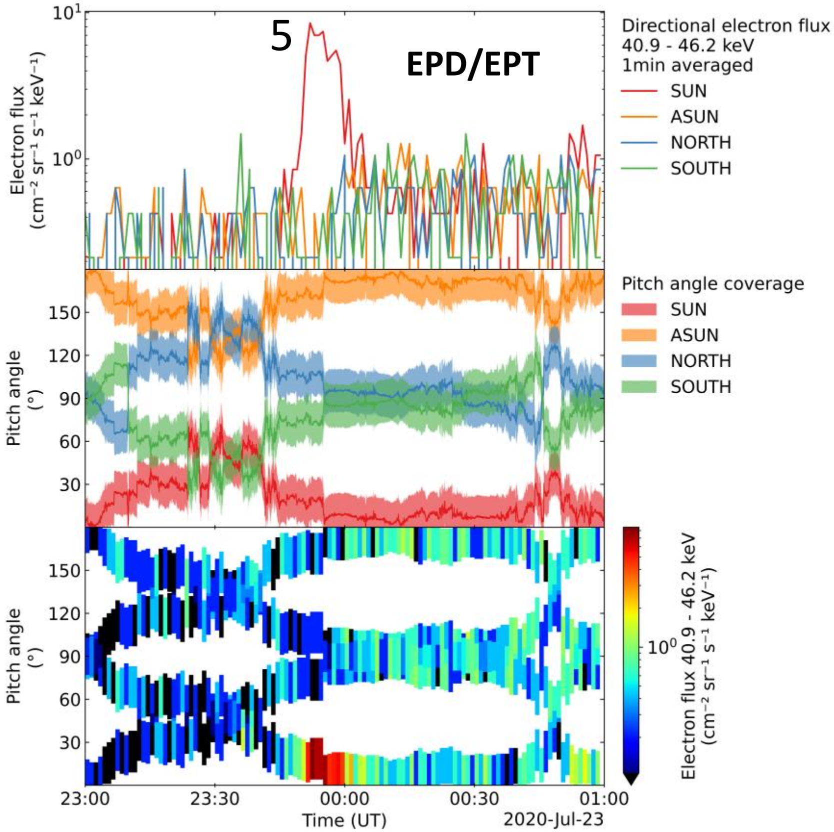
**2020 July 19, 20, 21**

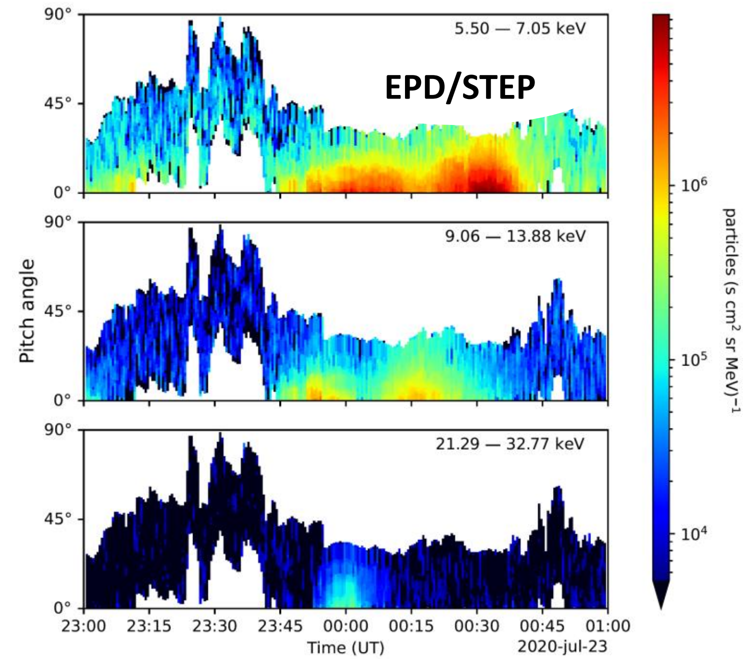


# First near-relativistic solar electron events observed by SolO/EPD

Gómez-Herrero,…,Malandraki et al. 2021, *A&A*

**2020 July 22**



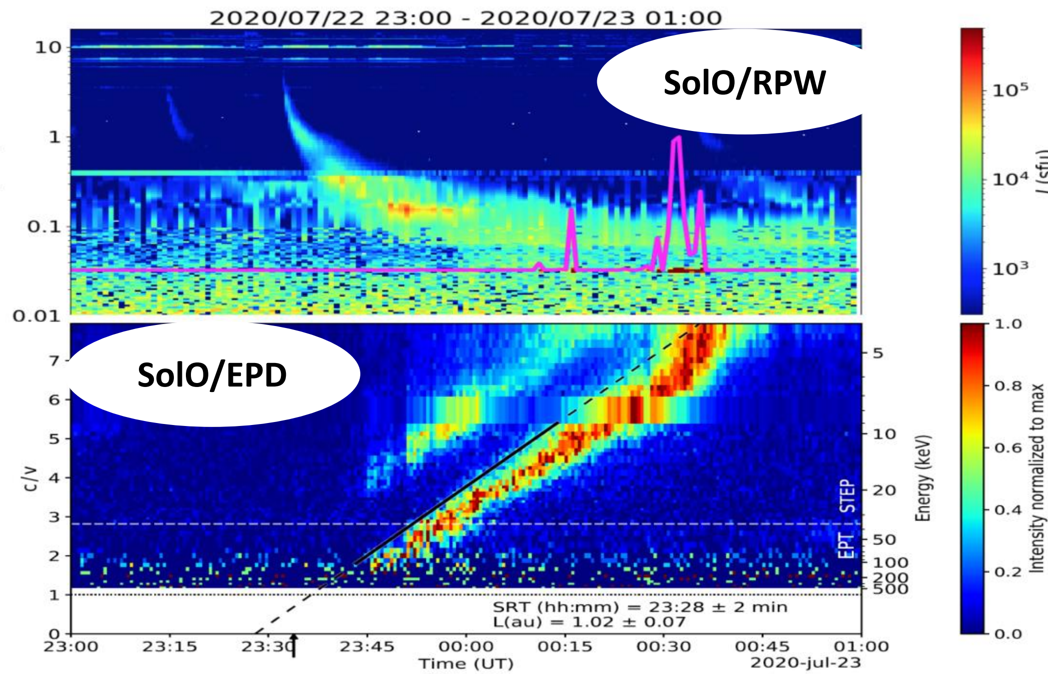

- **Jul 22**: EPT observed a very anisotropic $e^-$ event slightly >100 keV. A sharp onset with clear VD starting @ 23:40 UT ± 10 min (58 keV)
- The EPD Pitch Angle coverage was nearly optimal for this event

# First near-relativistic solar electron events observed by SolO/EPD

Gómez-Herrero,…,Malandraki et al. 2021, *A&A*

- Bottom: Inverse-speed vs time plot (VDA analysis) combining EPT and STEP $e^-$ data. Color scale represents the intensity
- 2 different injections were resolved at low energies, showing clear VDA and very narrow time profiles over the whole energy range
- Black slanted line: linear fit of the onset times at each energy bin >9 keV for 2nd injection. Onset times defined with 2σ method (Malandraki et al. 2012).
- Linear fit → estimation of effective path length and SRT @ the Sun.
- $L_{\text{Parker spiral}}$=0.77 AU << L = 1.02 AU (fit)
- Black arrow @ **23:34** UT: SRT shifted by the light propagation time to SolO
- tIII radio burst by RPW start time at **23:32** UT → only 2 min different to $e^-$ SRT

**2020 July 22**




- Magenta line: spectral flux around the local plasma frequency. Distinct peaks due to Langmuir waves locally generated when the $e^-$ beam causing the tIII radio burst reached the s/c location
- Observations support the existence of a direct magnetic connection to the solar source of the $e^-$

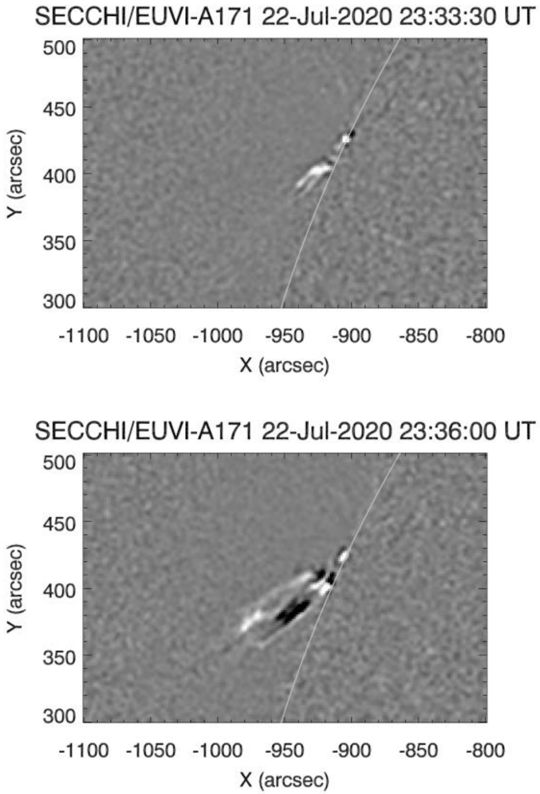
# First near-relativistic solar electron events observed by SolO/EPD

- SDO/AIA & ST-A/SECCHI EUV images examined: For all the events (except the weak Jul 19) sequence of multiple narrow ejections were found in 171, 195 and 304 Å EUV images, with appearance times very close to the $e^-$ onsets

- 2 ST-A/EUVI running difference images at 171 Å, showing a jet over the NE limb. Noteworthy is good agreement with the timing of the tIII radio burst at SolO and the $e^-$ SRT (as inferred by VDA)

**Gómez-Herrero,…,Malandraki et al. 2021**
***Solar Orbiter First results (Cruise Phase)***

**2020 July 22**

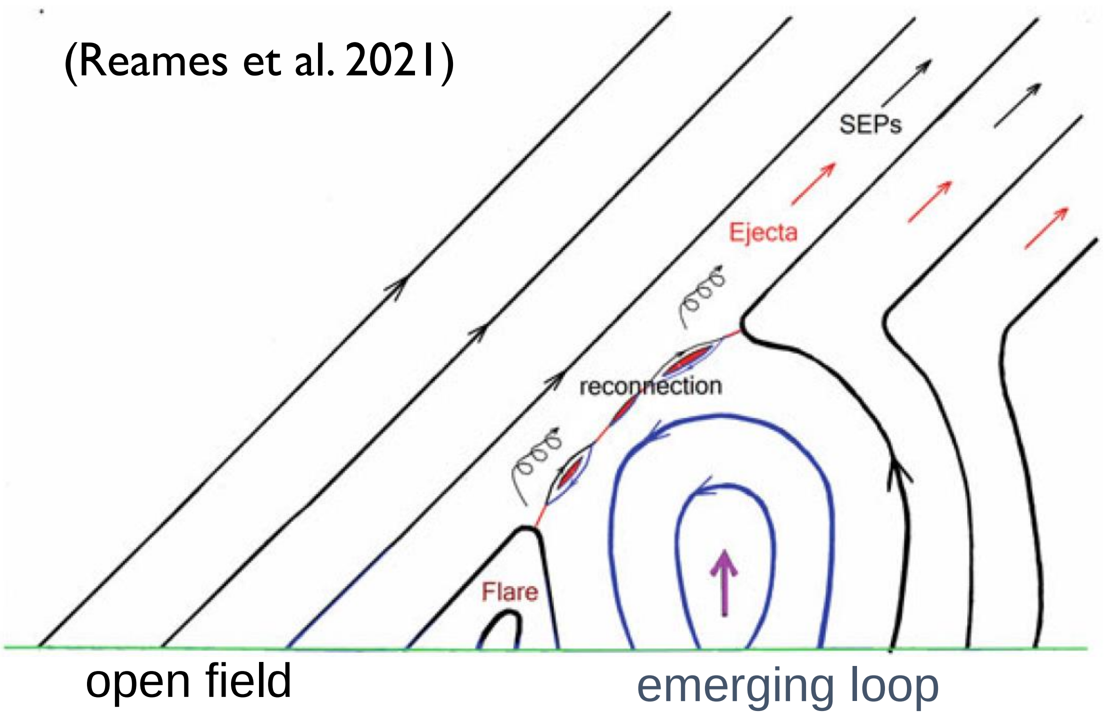


# Summary and Conclusions

- In spite of the solar min conditions, after its $1^{st}$ perihelion, SolO detected several NR $e^-$ events during 2020 July 11-24
- All of them were **clearly associated with tIII radio bursts observed by multiple s/c**
- **EUV jets** were observed with good time coincidence with the tIII radio bursts
- During the Jul 22 event, the observations support a very good connection to the source. However, although ST-A observed a jet at the East solar limb, the nominal magnetic footpoint connection was located more than **$30^o$** behind the East limb from the ST-A point of view
- The southward trajectory of the jet suggests non-radial coronal magnetic field lines which may help to explain how the narrow beam of energetic $e^-$ reached IMF lines connecting to **SolO at 0.69 AU.**
- There was **good time coincidence of the tIII radio bursts, the jet, and the inferred $e^-$ SRT**

# $^3$He-rich SEP events

(Reames et al. 2021)



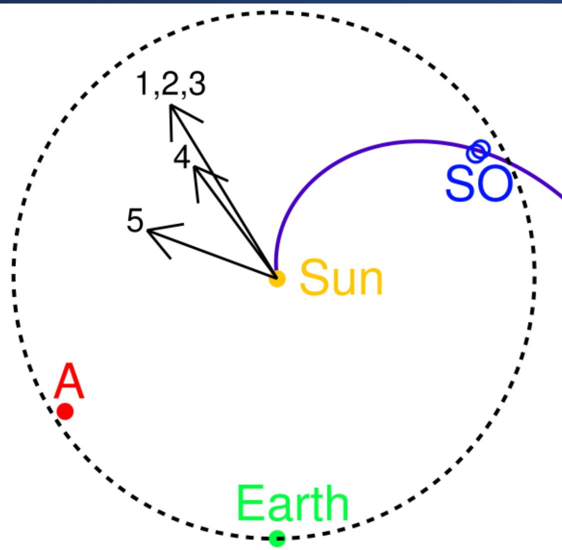

$^3$He-rich SEP events produced in Extreme Ultraviolet jets by a mechanism associated with magnetic reconnection

**Mason et al. 2020**

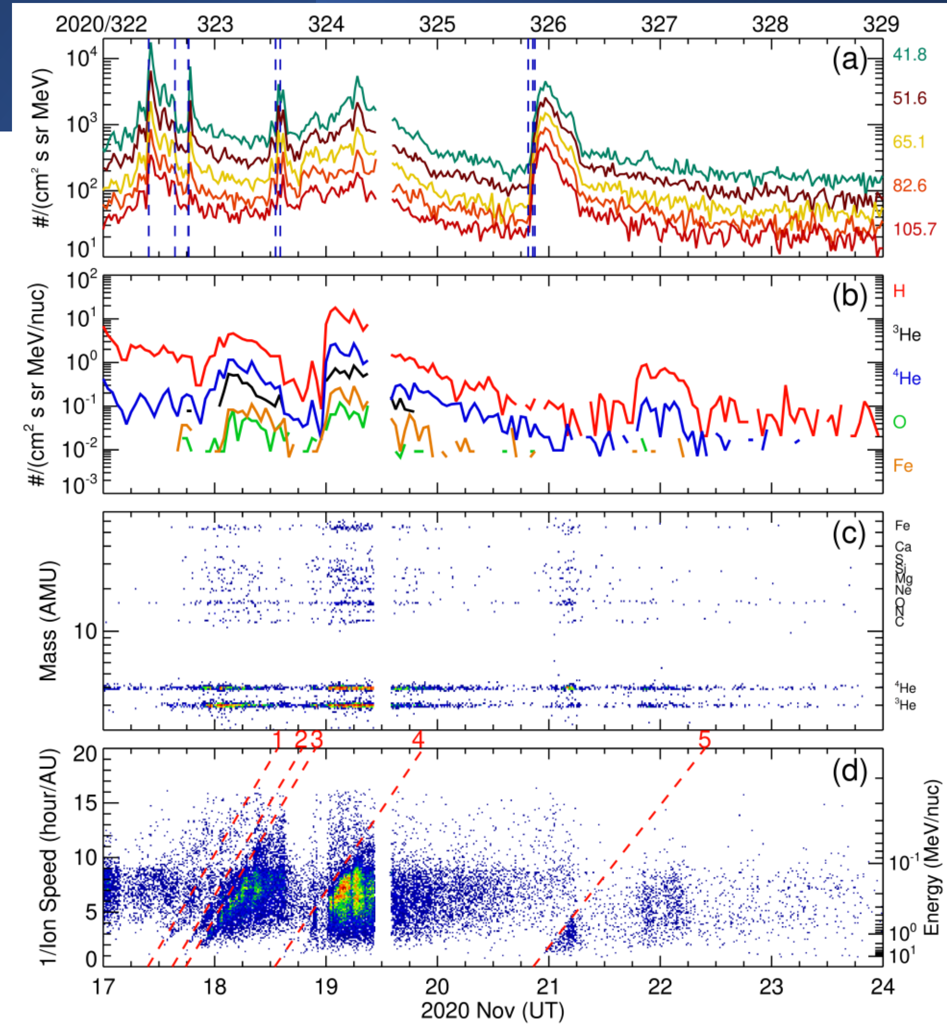
First SoLO $^3$He-rich SEP events measured during the s/c first perihelion pass from 0.52-0.96 AU in Jun-Sept 2020. 3/5 discrete events have a 0.2-2 MeV/nuc $^3$He/$^4$He above 10%, with a maximum **$^3$He/$^4$He of 0.61**.

# The long period of $^3$He-rich SEPs measured by SoLO 2020 Nov 17-23

Location of **SoLO** and **ST-A** shown 17-23 Nov, 2020. The angular separation between **SoLO** & **ST-A** = 180$^o$




- SoLO EPT and SIS measurements from Nov 17-23, 2020: 30-min electron intensities from 41.8-105.7 keV, hourly averages of the 0.23-0.32 MeV/nuc H, $^3$He, $^4$He, O and Fe intensities by SIS/EPD. Three major increases are seen. Mass spectrogram: almost continuous $^3$He presence for ~6.5 days
- Inverse ion-velocity time spectrogram: 5 injections. Arrows indicate the longitude of the solar source associated with the ion injections

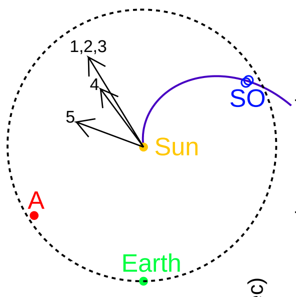



**Bučík et al. 2021, *A&A***

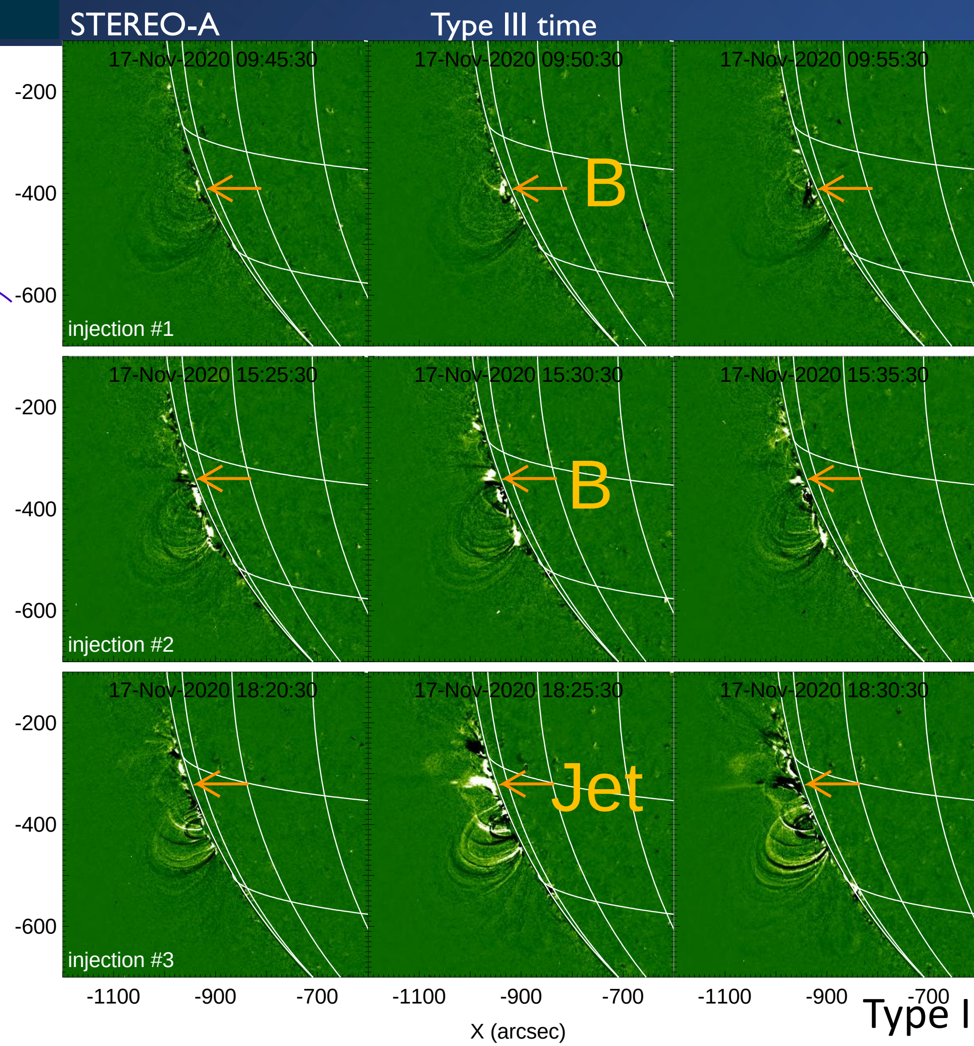
***Solar Orbiter First results (Cruise Phase)***

# The long period of $^3$He-rich SEPs measured by SoLO 2020 Nov 17-23 (*cntd.*)

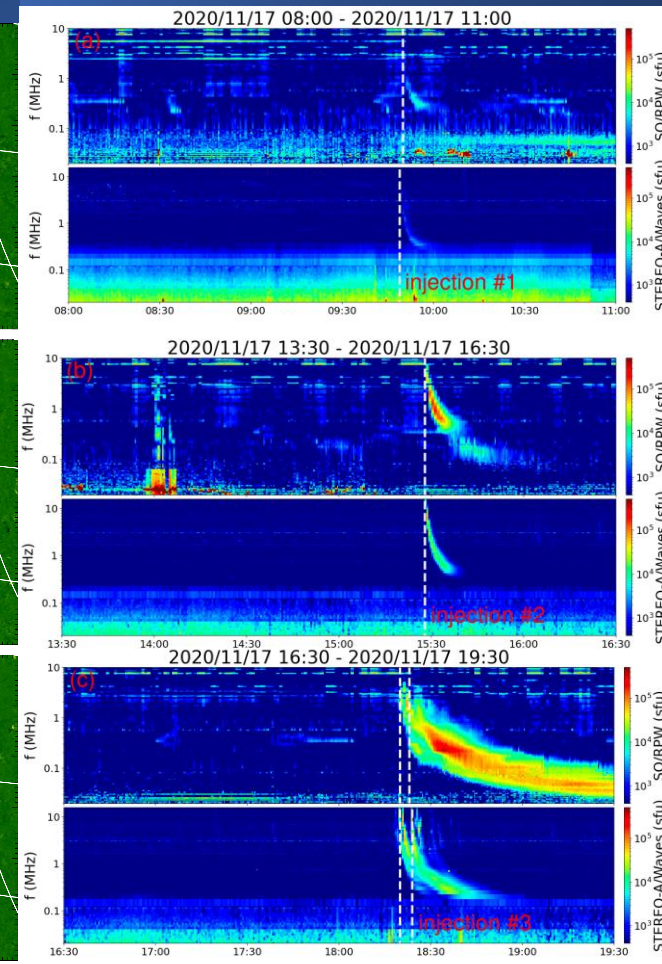
Injections #1,2,3




For the first 3 injections the type and location of the associated parent solar eruption as seen in the EUVI on ST-A is shown




J: a clear EUV jet, B: a brightening seen in the EUV images




Type III bursts associated with the ion injections. Multiple type III bursts appear to contribute to injections #3, #4 and #5

# The long period of $^3$He-rich SEPs measured by SoLO 2020 Nov 17-23

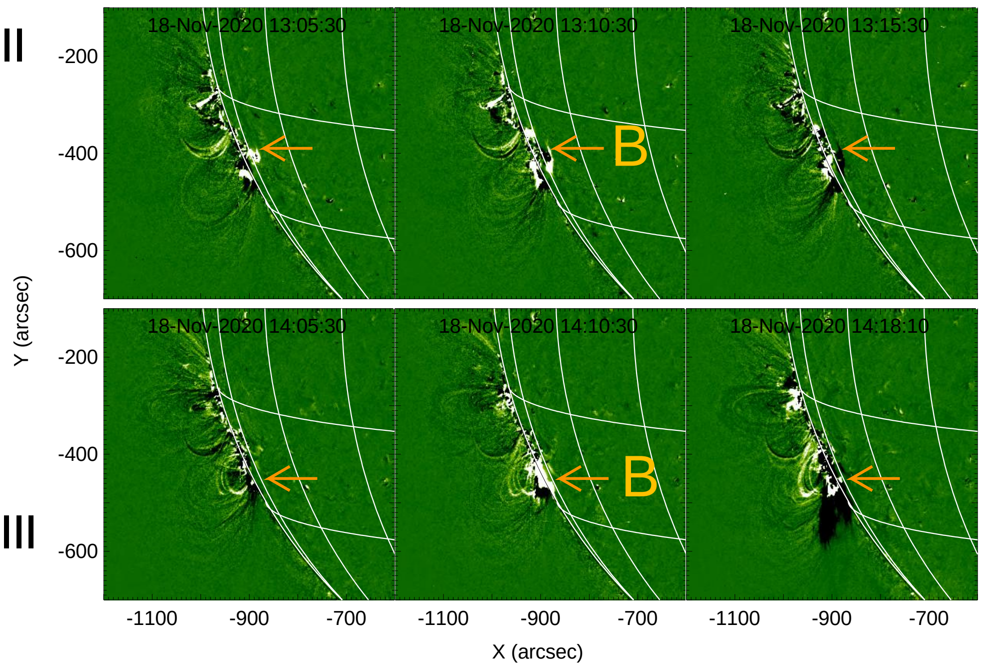
Jet

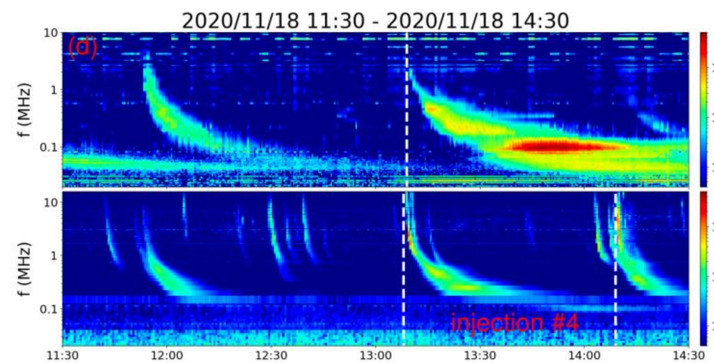
Injection #4

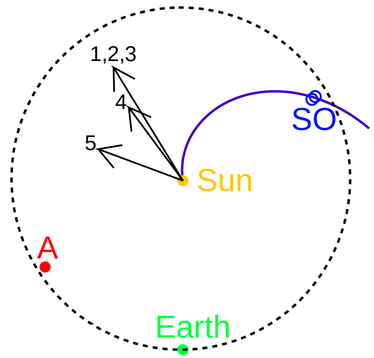
STEREO-A　　Type III time

1st Type III

2nd Type III




ST-A 195 Å EUV running difference images corresponding to injection #4. The arrow marks the solar source

**Bučík et al. 2021, *A&A***

# The long period of $^{3}$He-rich SEPs measured by SoLO 2020 Nov 17-23

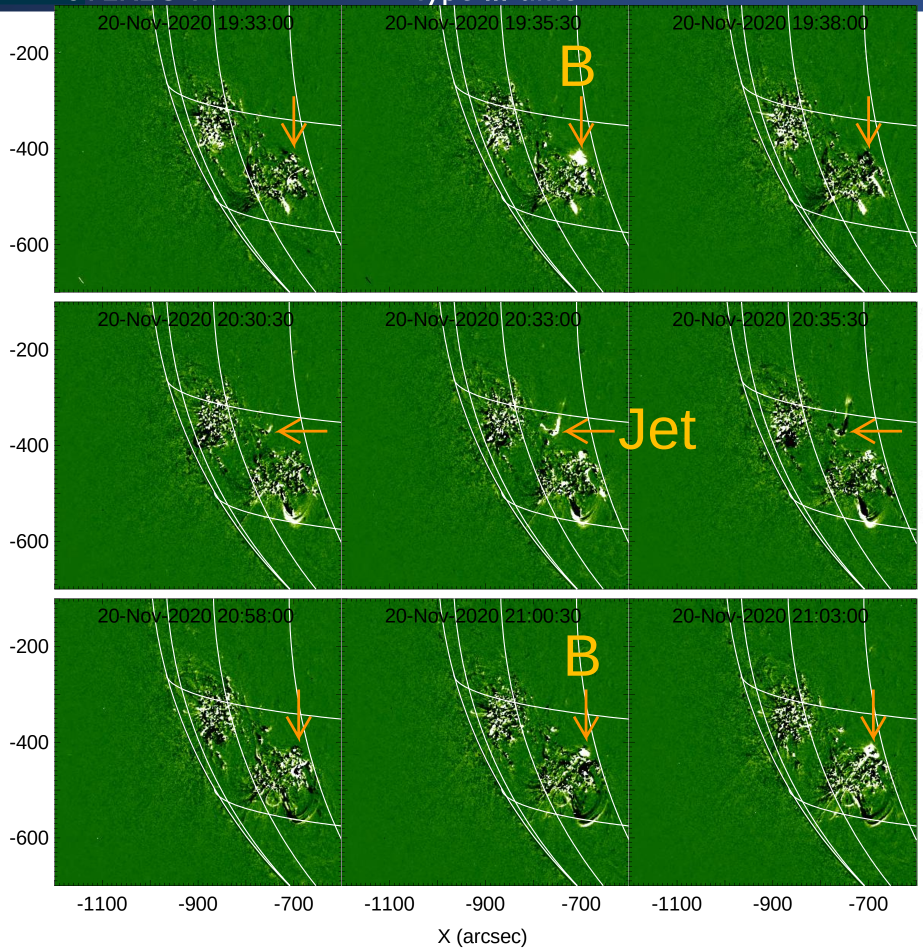
STEREO-A    Type III time

Injection #5

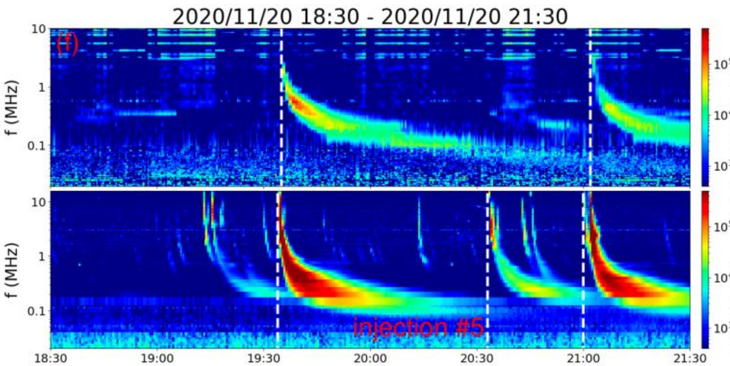
1st Type III

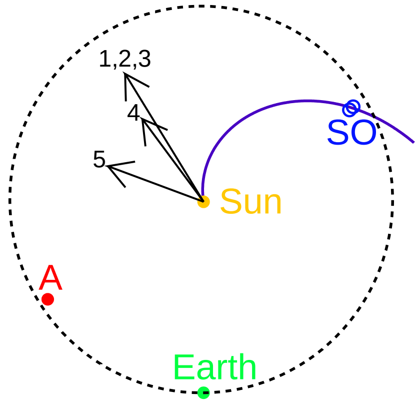
2nd Type III

3rd Type III




We clearly see the regions where activity comes from.

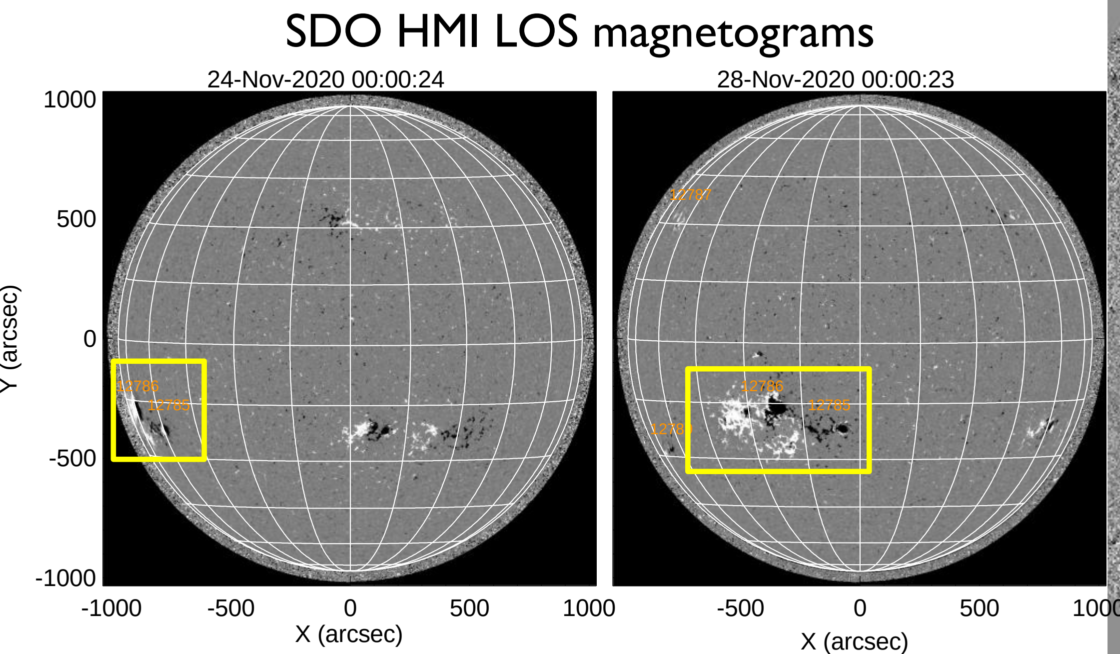


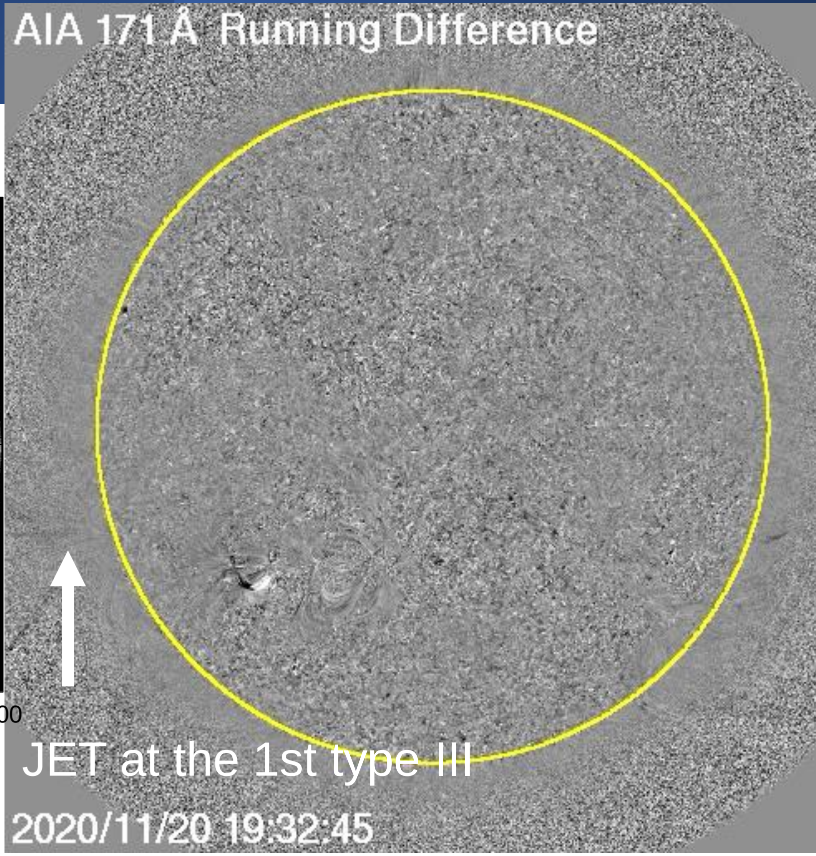




SDO was not located at a good position to observe EUV activity related to the origin of these ion injections.

**Bučík et al. 2021, *A&A***

# The long period of $^3$He-rich SEPs measured by SoLO 2020 Nov 17-23




SDO HMI magnetograms on Nov 24 and Nov 28: The EUV activity observed by ST-A Nov 17-20 likely originated in two adjacent large ARs 12785 and 12786 that appeared near the east limb, as viewed from the Earth early on Nov 23.

For injection #5: the SDO/AIA observed the EUV jets, from the region ~16 deg behing the east limb, that temporally match all type III bursts

**Bučík et al. 2021, *A&A***

# Conclusion

• the long period of $^{3}$He-rich SEPs observed by SoLO related to the recurrent jets & brightenings in a large and complex group of sunspots in two adjacent ARs

• such configuration may be favorable for the recurrent particle injections in the sense that there may be a long-lived interaction between the negative polarity of one AR and the positive polarity of the neighboring AR, leading to the magnetic reconnection

• two ARs produce a longitudinally extended source (~40°) in which spacecraft may be magnetically connected for a long period as the Sun rotates

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*

*Solar Orbiter First results (Cruise Phase)*

- Overview of particle observations from 2020 Nov 28-Dec 3 collected by SolO, PSP, ST-A and L1
- Each panel: intensity time profiles of $e^-$ (upper) and $p^+$ (lower)
- View of the ecliptic from solar North: s/c locations on Nov 29 ~ 13:00 UT ~ time of onset of the SEP event
- S/C covered a longitude span of ~**238º.** Intensity increases of **$p^+$ > 50 MeV** and **$e^-$ > 1 MeV** clearly observed
- Nominal Parker spiral IMF lines connecting each s/c with the Sun. STEREO/PLASTIC AND Wind/SWE solar wind speed used. For PSP and SolO speeds obtained from ENLIL simulations used instead
- M4.4 SXR flare NOAA AR located just behind the East limb (as viewed from Earth) (black arrow) ST-A: **E98S23**

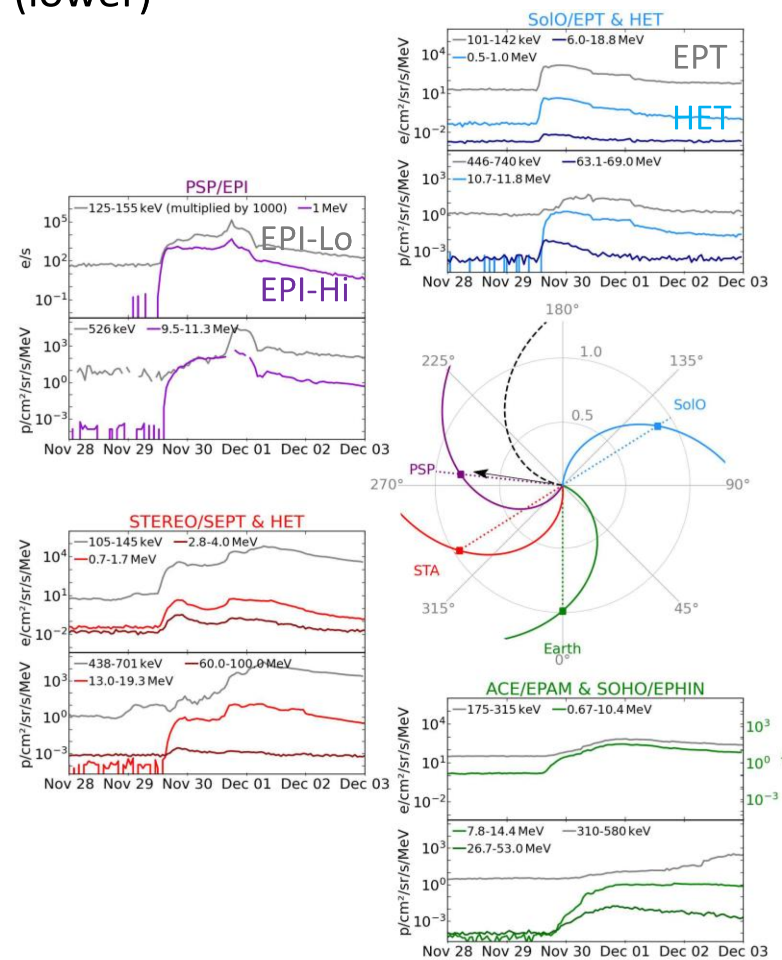



Table 1: Spacecraft locations, magnetic field footpoints, IMF path length (L) and longitudinal separation (ΔLon.) from the flare location (HGC: 249° longitude; -23° latitude)

| Location[a] | | | | Magnetic field footpoints[a] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Parker Spiral | | | | | ENLIL[b] | | | |
| Spacecraft/Body | r (AU) | Lon. | Lat. | Vsw(km $s^{-1}$) | Lon. | Lat. | ΔLon. | L(AU) | Lon. | Lat. | ΔLon. | L(AU) |
| STEREO-A | 0.96 | 290° | 7° | 361 | 355° | 7° | 106° | 1.15 | 344° | 6° | 95° | 1.16 |
| Earth | 0.99 | 348° | 1° | 358 | 55° | 1° | 166° | 1.18 | 44° | 1° | 155° | 1.24 |
| PSP | 0.81 | 251° | 4° | 295[b] | 319° | 4° | 69° | 0.98 | 298° | 4° | 49° | 0.94 |
| Solar Orbiter | 0.88 | 110° | -5° | 417[b] | 162° | -5° | -88° | 1.0 | 145° | -6° | -104° | 0.94 |

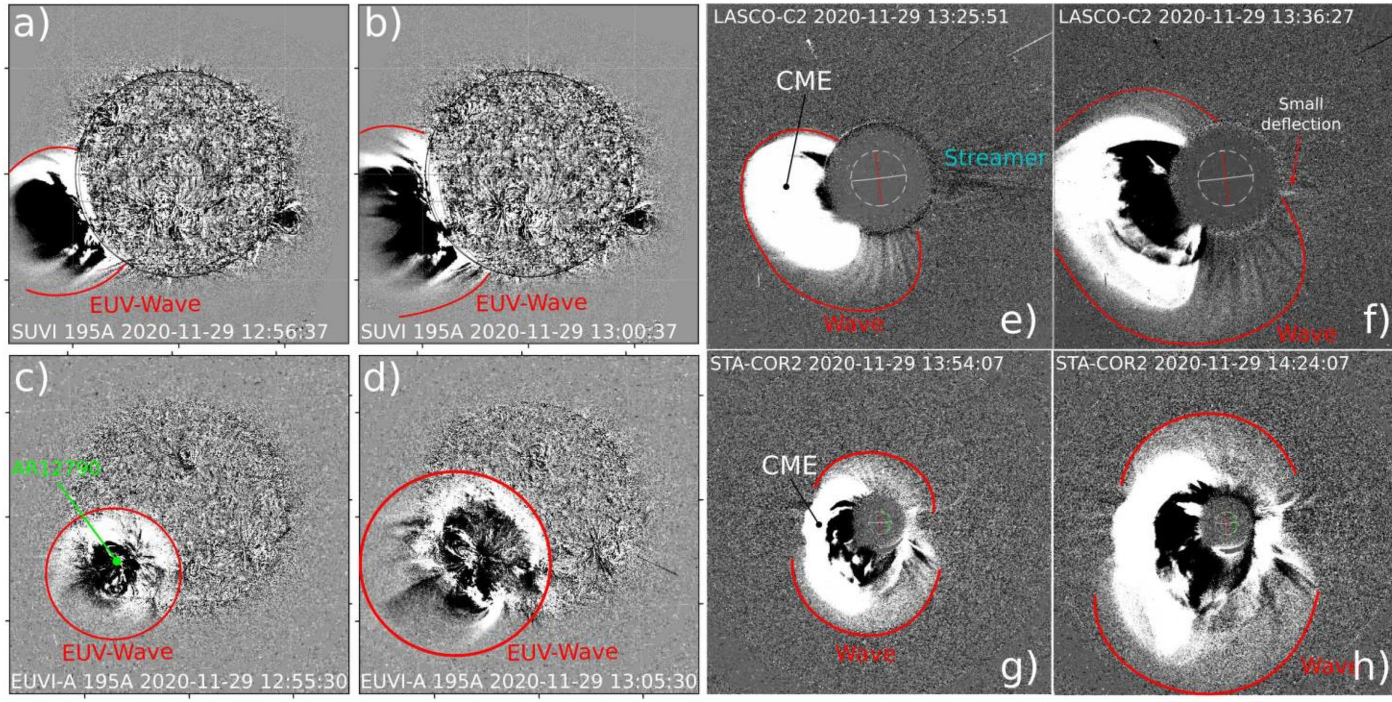
[a] Coordinates are given in the Carrington Heliographic (HGC) system. [b] ENLIL values are taken from simulation on 29/11/2020 at 13:00 UT. Path length calculated for ENLIL magnetic field lines assume a radial extension from 21.5 $R_\odot$ to 1 $R_\odot$.

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*

*Solar Orbiter First results (Cruise Phase)*

- Remote sensing observations of the EUV wave, the CME and the white-light shock wave observed from two different viewpoints
- Running difference images of SUVI (Panels a, b) and ST-A EUVI (Panels c, d) at 195 Å taken during the early stage of the EUV wave expansion in the low corona. Front of EUV wave outlined with red lines
- EUV wave measured to propagate on the solar disk with average V = 500km/s.




- ❖ White-light coronagraphic observations recorded a fast and relatively wide CME together with a shock wave observed as a bright front around the CME. Running difference images in white light from SOHO/LASCO-C2 (panels e and f) and ST-A/COR-2 (g and h). CME is labeled and white-light shock wave is labeled and outlined with red lines

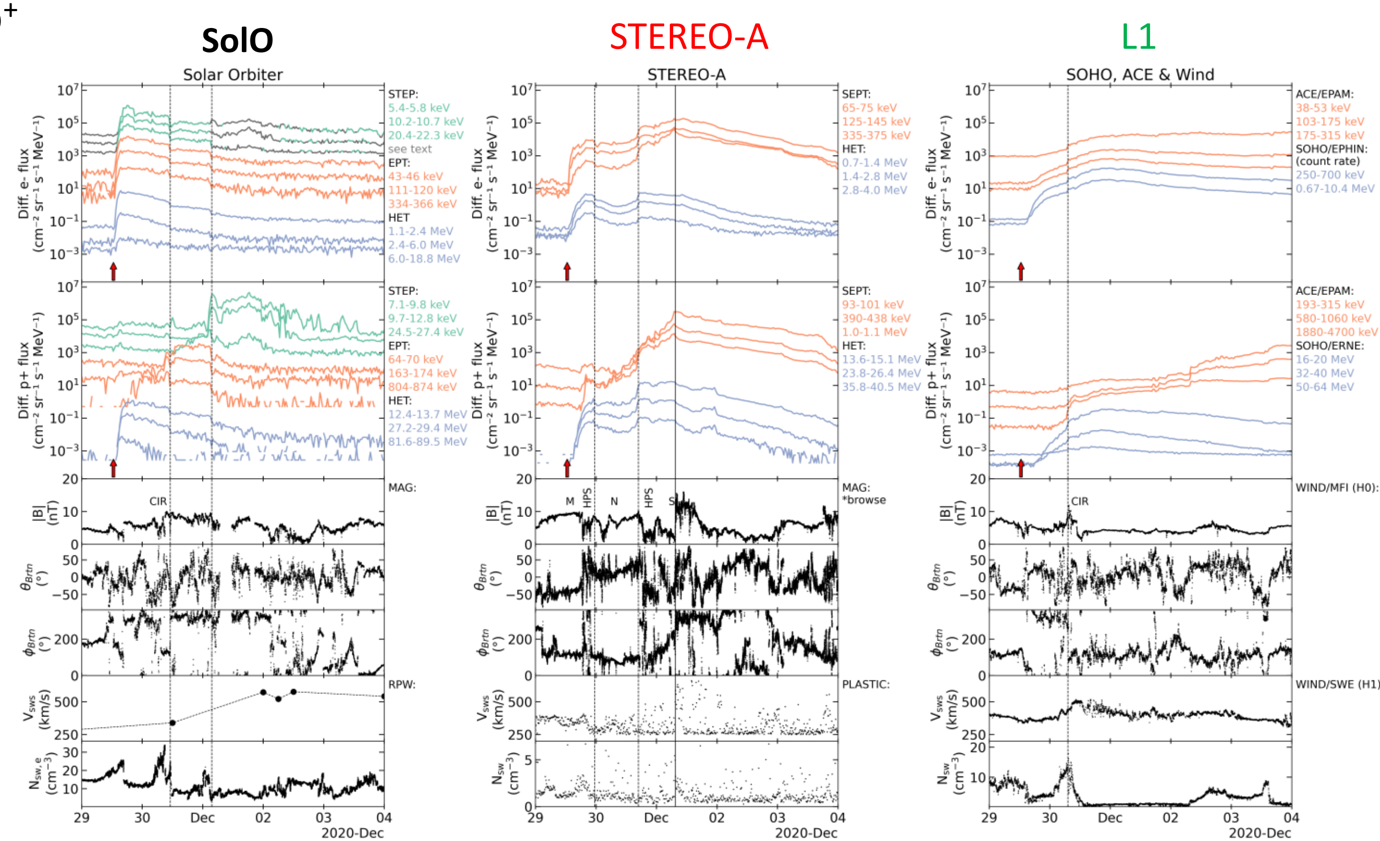
- ❖ From 3D reconstruction: Vradial (CME)=~1500km/s, Vradial (SW) =~1800km/s

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*

*Solar Orbiter First results (Cruise Phase)*

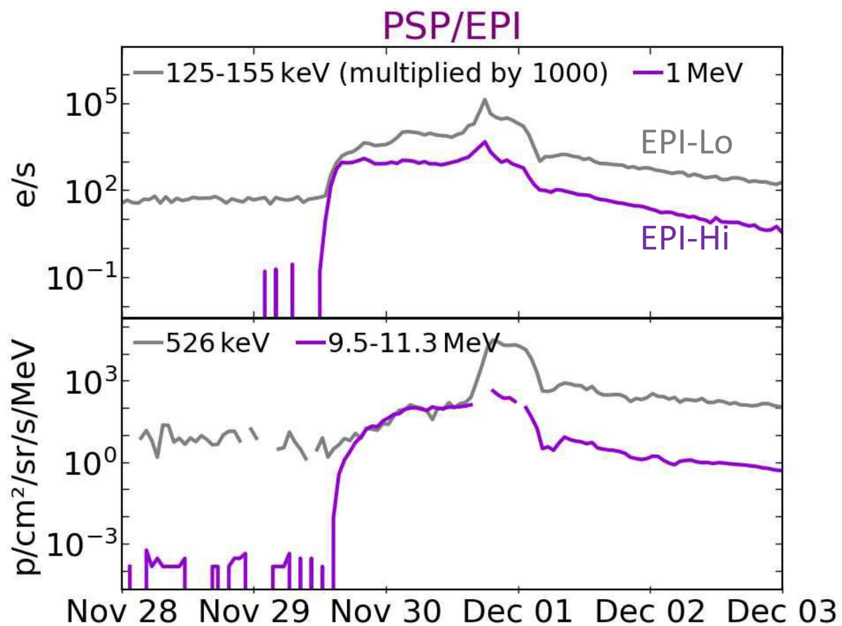
- SolO $e^-$ and high energy $p^+$ (>12 MeV): A rapid rise shortly after parent solar eruption (red vertical arrow) followed by a gradual decay. Typical of SEP events originating from Western longitudes relative to observing s/c
- ST-A: Particle intensities show a similar response to parent solar eruption but profiles are more irregular than at SolO.
- L1: Particle intensities show a more gradual increase with an onset substantially delayed w.r.t other s/c




- SEP intensity time-profiles by the 3 s/c were also affected by the passage of local solar wind structures (e.g. CIRs, multiple sector boundary crossings)

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*
*Solar Orbiter First results (Cruise Phase)*



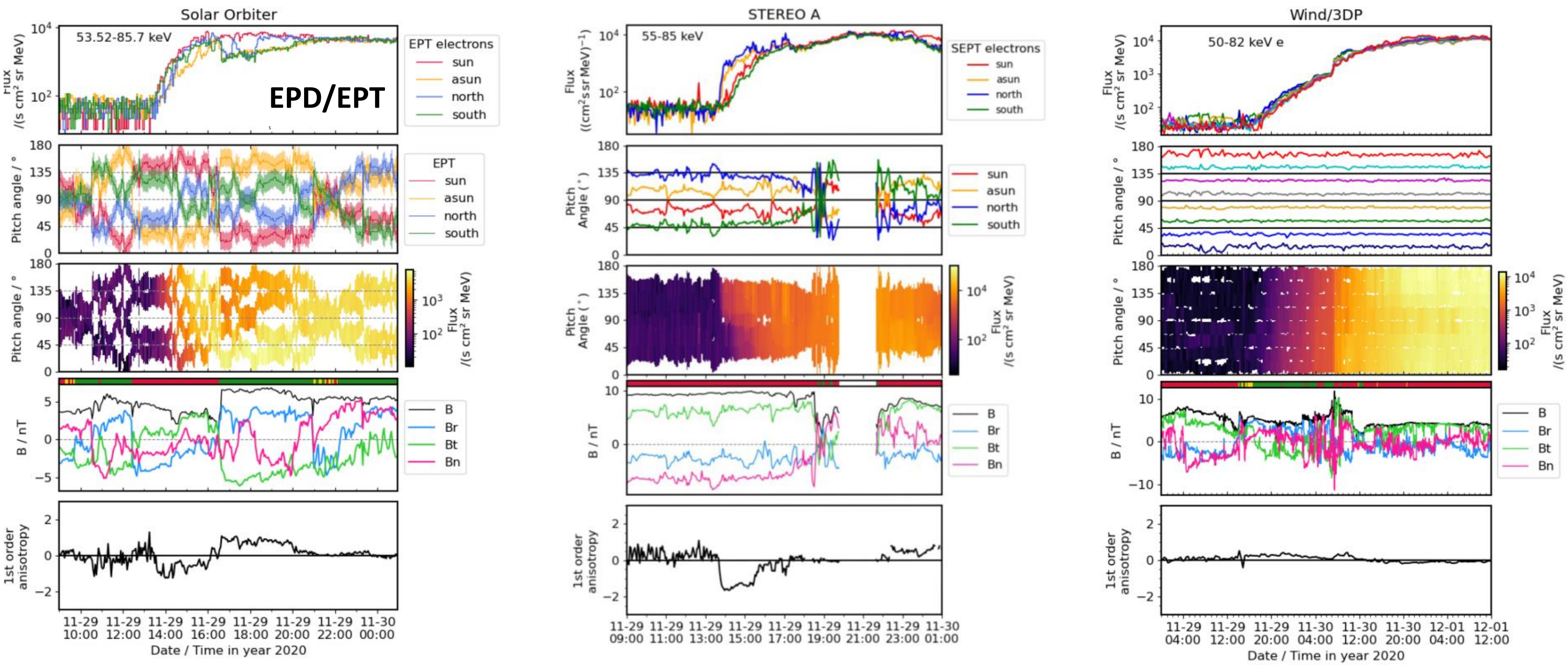

PSP, Cohen et al. 2021

- 10 MeV $p^+$ intensity and 1 MeV $e^-$ count rates rise fairly quickly after the tIII radio burst associated with the M4.4 flare. The 0.5 MeV $p^+$ and 150 keV $e^-$ show a more gradual increase
- Region around the shock arriving at PSP sufficiently turbulent that the 0.5 MeV $p^+$ well confined and strongly peak at the time of the shock passage
- Peak of the $e^-$ c/s coincident with the shock arrival: Possibly are a trapped population due to the narrow region between this and a preceding ICME
- Following passage of S and sheath SEP intensity drops dramatically as PSP enters ICME (typical)

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*

*Solar Orbiter First results (Cruise Phase)*




❖ e⁻ PADs, First order anisotropy:

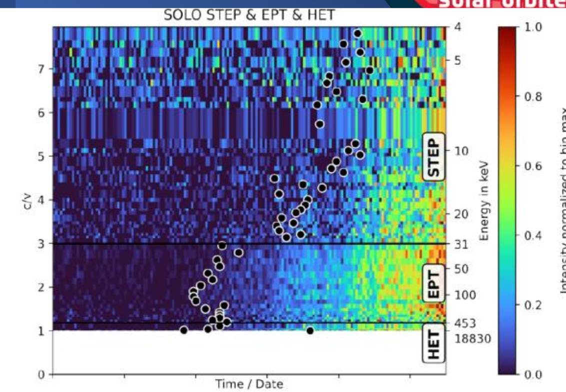
**<u>Wind:</u>** a very weak anisotropy due to anti-SW propagating e⁻, **<u>SolO:</u>** stronger anisotropy, expected due to its much smaller longitudinal separation angle to the parent solar AR**, <u>ST-A</u>**: largest anisotropy observed surprising since s/c far separated (~95) from the parent AR. However, since Langmuir waves were detected locally at ST-A, so large anisotropy is expected

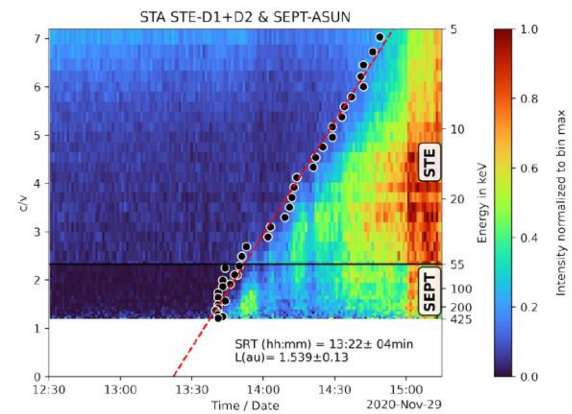
# The First widespread SEP event observed by SolO on 2020 Nov 29

Table 2: Timeline of the 2020 November 29 SEP event.

| Date | Estimated solar release time (UT) | Delay w.r.t. Type III(1) (min) | Observed onset time (UT) | Observation | Instrument | Mission |
|---|---|---|---|---|---|---|
| 29/11 | 12:26 | -19 | 12:34 | M4.4 X-ray flare onset | GOES | GOES |
| 29/11 | 12:37 | -8 | 12:45 | hard X-ray onset | EPHIN | SOHO |
| 29/11 | 12:43 | -1 | 12:51 | dm-m-λ type II | ORFEES | Earth |
| 29/11 | 12:45 | 0 | 12:53 | DH type III(1) | WAVES | STA |
| 29/11 | 12:58 | +13 | 13:06 | DH type II | WAVES | STA |
| 29/11 | 12:58 | +13 | 13:06 | DH type III(2) | WAVES | STA |
| 29/11 | 13:03 | +18 | 13:11 | M4.4 X-ray flare max | GOES | GOES |
| 29/11 | 13:17 | +32 | 13:25 | CME | COR2 | STA |
| 29/11 | 13:19± 5 min TSA | +34 | 13:28± 5 min[c] | > 0.5 MeV e- onset | EPI-Hi | PSP |
| 29/11 | 13:22± 4 min VDA | +37 | 13:39± 1 min | 165 – 335 keV e- onset | SEPT | STA |
| 29/11 | 13:17±11 min TSA[a,b] | +32 | 13:40±11 min | 168 – 334 keV e- onset | EPT | SolO |
| 29/11 | 15:24±19 min TSA[a] | +159 | 15:36±19 min | 250 – 700 keV e- onset | EPHIN | SOHO |
| 29/11 | 13:15 VDA[c] | +30 | 14:30± 5 min[c] | 8.0 – 16.0 MeV p onset | EPI-Hi | PSP |
| 29/11 | 13:53± 5 min TSA[a] | +68 | 14:35± 5 min | 13.7 – 21.2 MeV p onset | HET | SolO |
| 29/11 | 14:47±10 min TSA[a] | +122 | 15:40±10 min | 13.6 – 19.3 MeV p onset | HET | STA |
| 29/11 | 18:54± 5 min TSA[a] | +369 | 19:50± 5 min | 13.0 – 20.0 MeV p onset | ERNE | SOHO |

[a] Assuming the path length from ENLIL simulations listed in Table 1.
[b] The onset of 165 – 334 keV electrons observed by EPT is likely too late due to a low signal-to-background ratio. Here we are using the earliest onset time of relativistic electrons (2.4 – 6.0 MeV) observed by HET at 13:25 UT for the TSA.
[c] Values for PSP were taken from Cohen et al. (2021).




- VDA performed: c/v vs. time plots, upper: STEP, EPT and HET on SolO , bottom: STE, and SEPT on ST-A. Black points mark the onset times of each energy channel
- ST-A: linear fit → SRT: 13:22 ± 4 min, $L_{effec}$=1.54 ± 0.13 AU, onset times follow a clear dispersion, in agreement with linear fit. The onset times derived for SolO more ambiguous due to smaller geometry factors of SolO/EPT and STEP and instrumental issues involved

- TSA performed for 2.4-6.0 MeV HET $e^-$ (earliest observed onset at 13:25 UT & L from ENLIL)

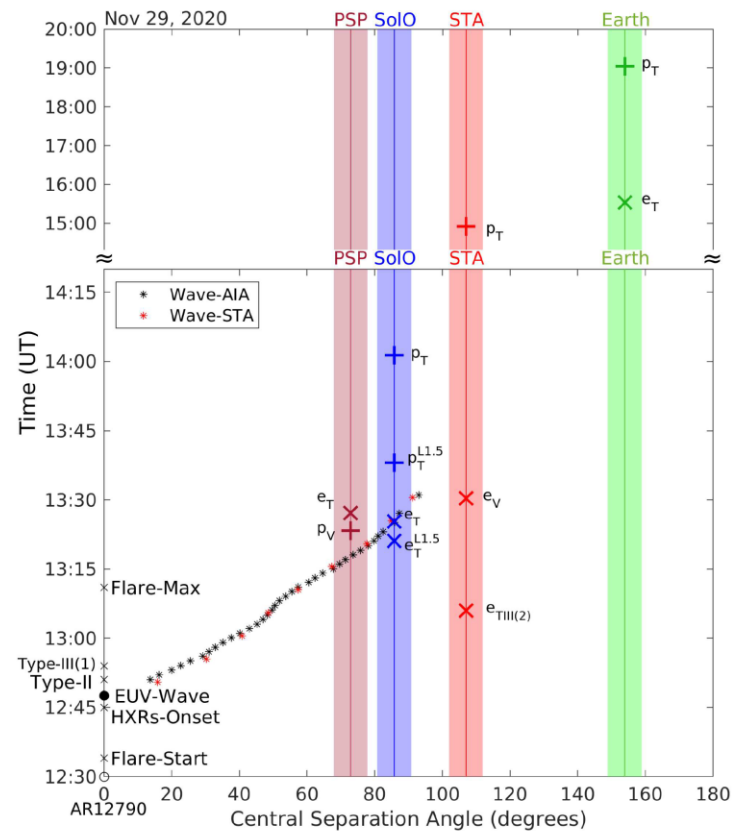
**Kollhoff,…,Malandraki et al. 2021, *A&A Solar Orbiter First results (Cruise Phase)***

# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*
*Solar Orbiter First results (Cruise Phase)*

## Timing of energetic particles – Interpretation 1

- **No clear relationship is found between the release times of the EP for each s/c with the arrival times of the EUV wave at the corresponding field line footpoints**
- The significant anisotropy of the first arriving $e^-$ and the detection of Langmuir waves at ST-A provide evidence that **non-nominal magnetic connections** are an important element of this widespread event
- Uncertainties in the TSA might be significant: A prolongation of the path length for protons caused by a turbulent random-walk or by the meandering of field lines in the corona and IP space (modeled by Laitinen and Dalla, 2019). → increase the $p^+$ path lengths from those assumed in TSA →reduce the time differences between the $p^+$ release times and the EUV wave connections times

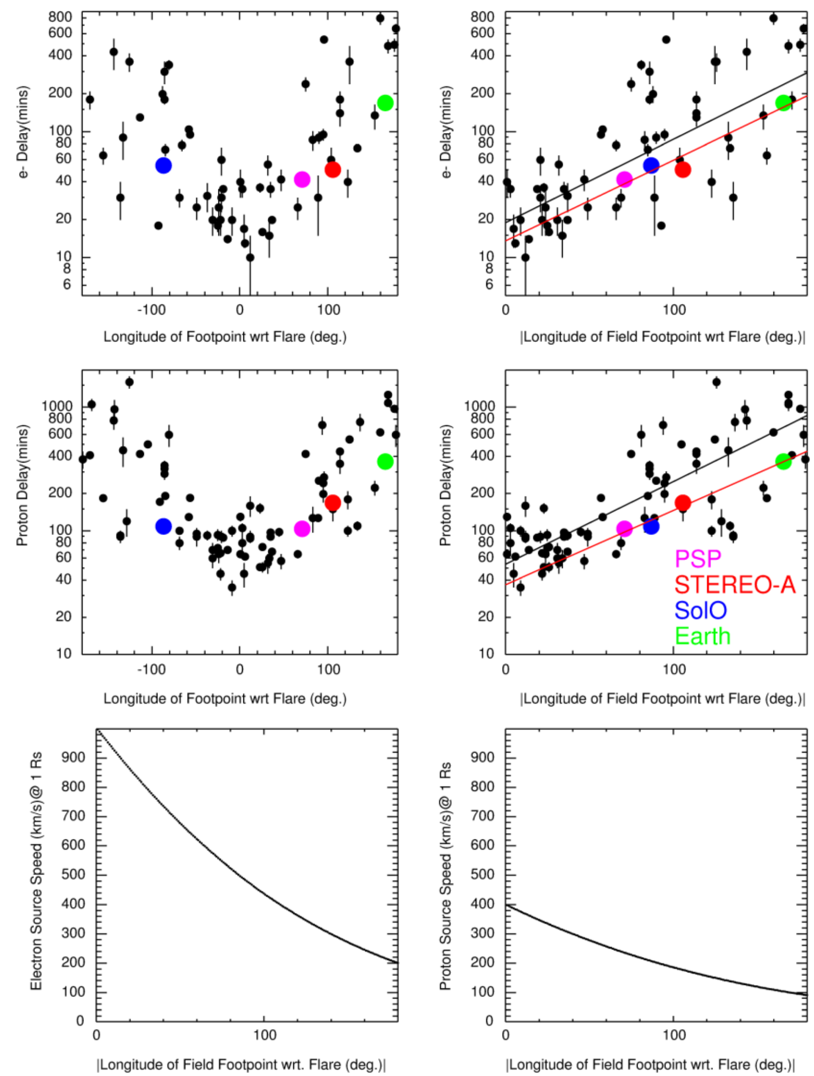


# The First widespread SEP event observed by SolO on 2020 Nov 29

Kollhoff,…,Malandraki et al. 2021, *A&A*
*Solar Orbiter First results (Cruise Phase)*

## Timing of energetic particles – Interpretation 2

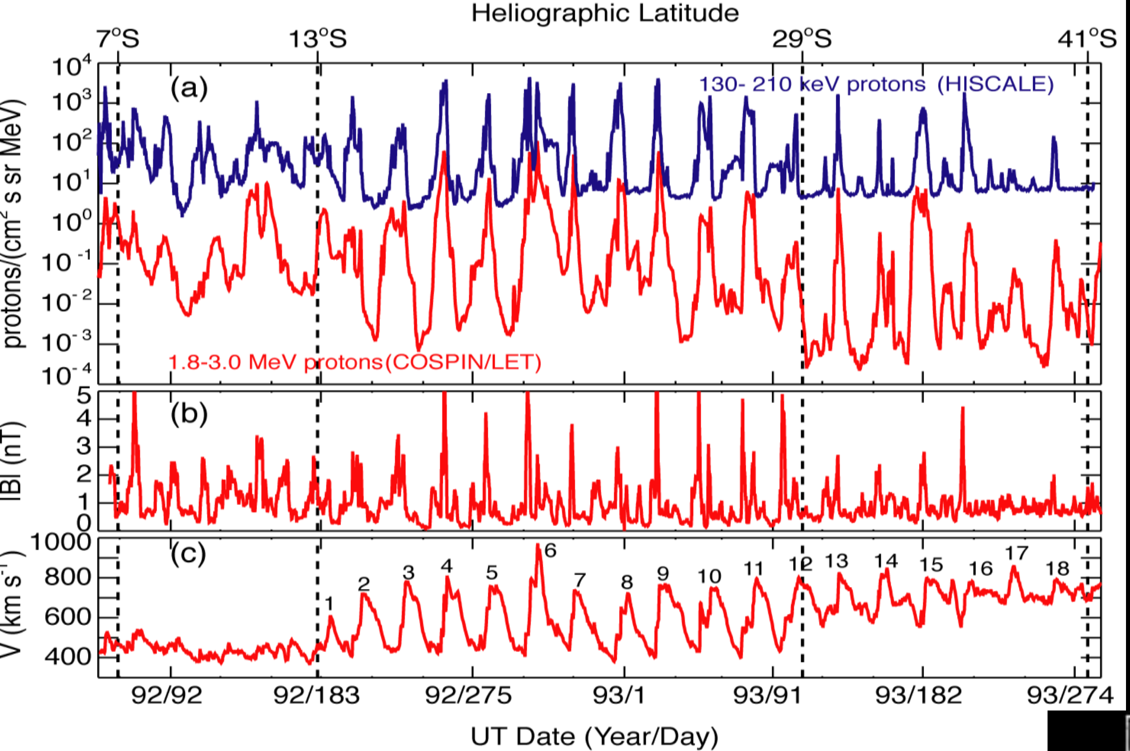
- **Richardson et al. 2014**: NR electron delays vs connection angle for the SC 24 event → general increase in the onset delay with increasing connection angle. Colored circles for Nov 2020 show **similar results** for $e^-$ (top) & $p^+$ (middle)
- Different source speeds suggest that the electron and proton onset delays **cannot be accounted by a connection to a single particle source**

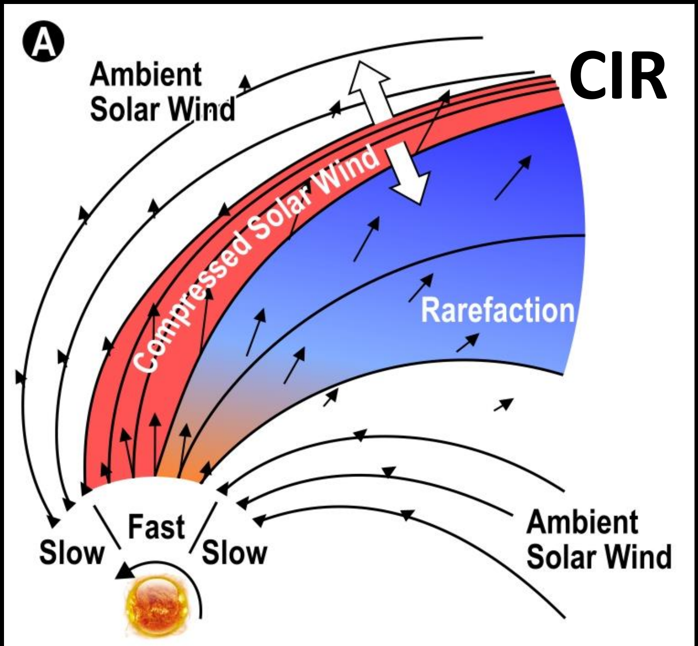


# Summary

- ✓ On 2020 Nov. 29 SolO has observed its first wide-spread event, which was also the first wide-spread event of solar cycle 25
- ✓ Electrons >1MeV and protons >50MeV were observed at widely separated locations spanning ~230° in heliolongitude and 0.81–0.99 AU in heliocentric distance
- ✓ The event was accompanied by a class M4.4 flare, multiple Type II and Type III bursts, an EUV wave and a CME
- ✓ Comparing the EUV wave propagation and the solar release times we found no clear relationship of their timing (considering the simple scenario presented)
- ✓ The observed onset delays are comparable to those observed at similar SEP events during solar cycle 24 → scenario of efficient cross-field transport of particles could be the dominant process leading to broad longitudinal particle spread at 1 AU
- ✓ A combination of these scenarios cannot be ruled out

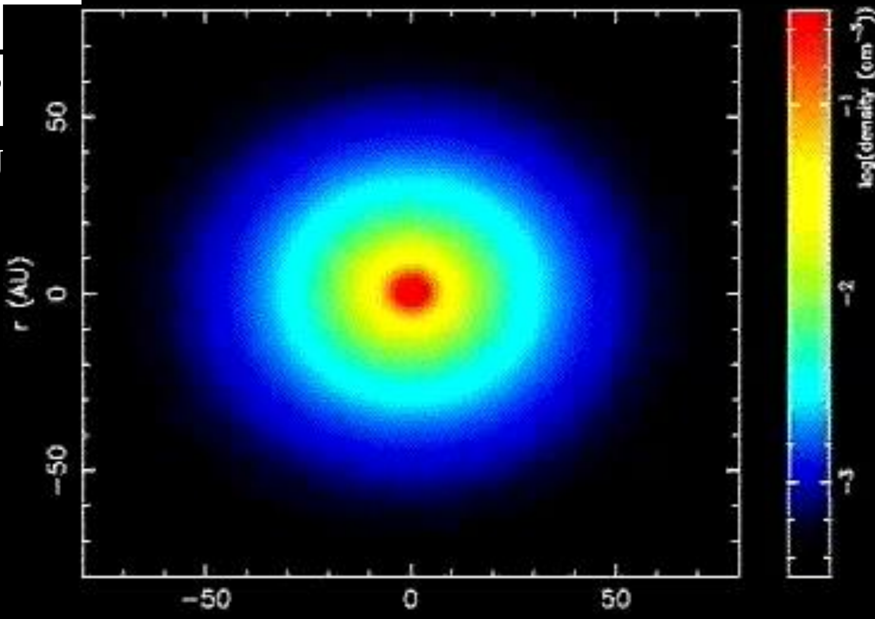
# Corotating Interaction Region-Related Populations

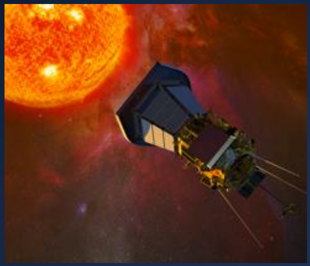



*Desai et al. 2000; Desai 2019, Malandraki et al. 2007, 2008*

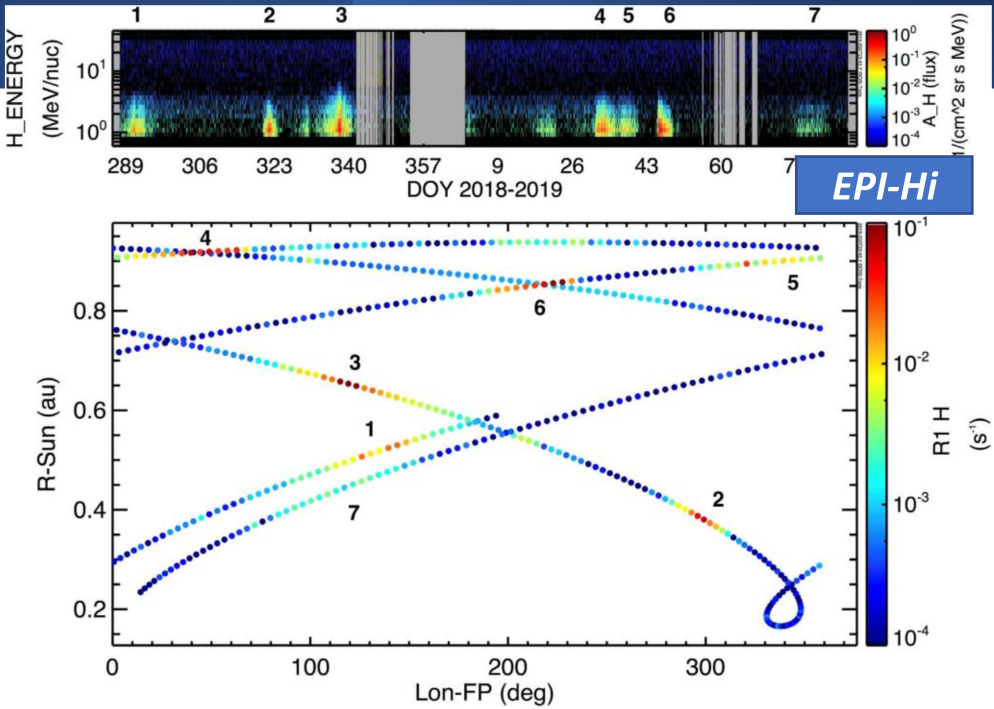
- Bounded by Forward-Reverse shocks between ~2-5 AU
- **Fisk and Lee (1980) model**: EP accelerated at the shock region and transported back inward toward the observer
- Energetic Protons recur ~26 days
- Helios 5 CIR-associated events < 0.6 AU (Van Hollebeke et al. 1978)
- PSP/ISOIS & SolO/EPD appropriate instruments (e.g. to distinguish between He & H)





# *PSP Orbits 1,2:* Energetic Particle Increases Associated with SIRs

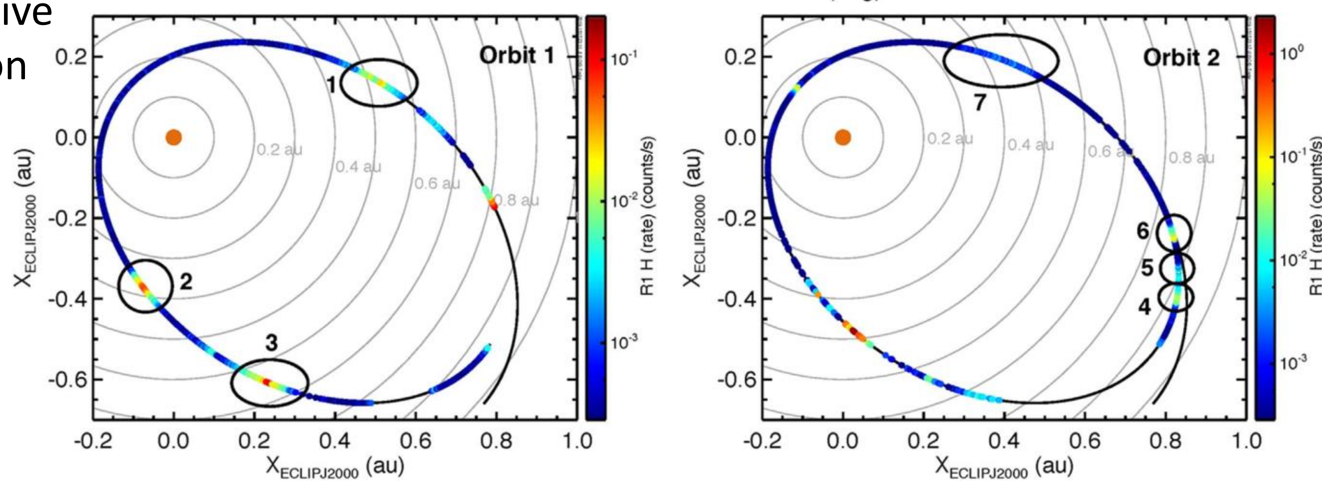
Cohen et al. 2020, *ApJS*

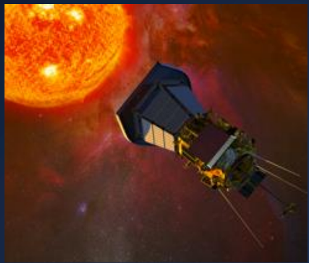



- ❑ $P^+$ intensity spectrogram from **EPI-Hi/LETA**: events relatively small with $p^+$ increases up to a few MeV but last for several days
- ❑ Heliocentric distance of PSP vs. calculated footpoint. Color intensity **1-2 MeV LETA $p^+$**
- ❑ Events 1 & 3 at about the same solar footpoint longitude → **CIR**
- ❑ Event 7 later → maybe separate and unrelated

<ins>Allen et al. 2020 *ApJS*</ins>: the stream interfaces of Events 2 and 3 arrive at ST-A after further corotation

- ➢ **7** particle increases observed by ISꙨIS/EPI-Hi during first two PSP orbits
- ➢ **Two are inside 0.5 AU**





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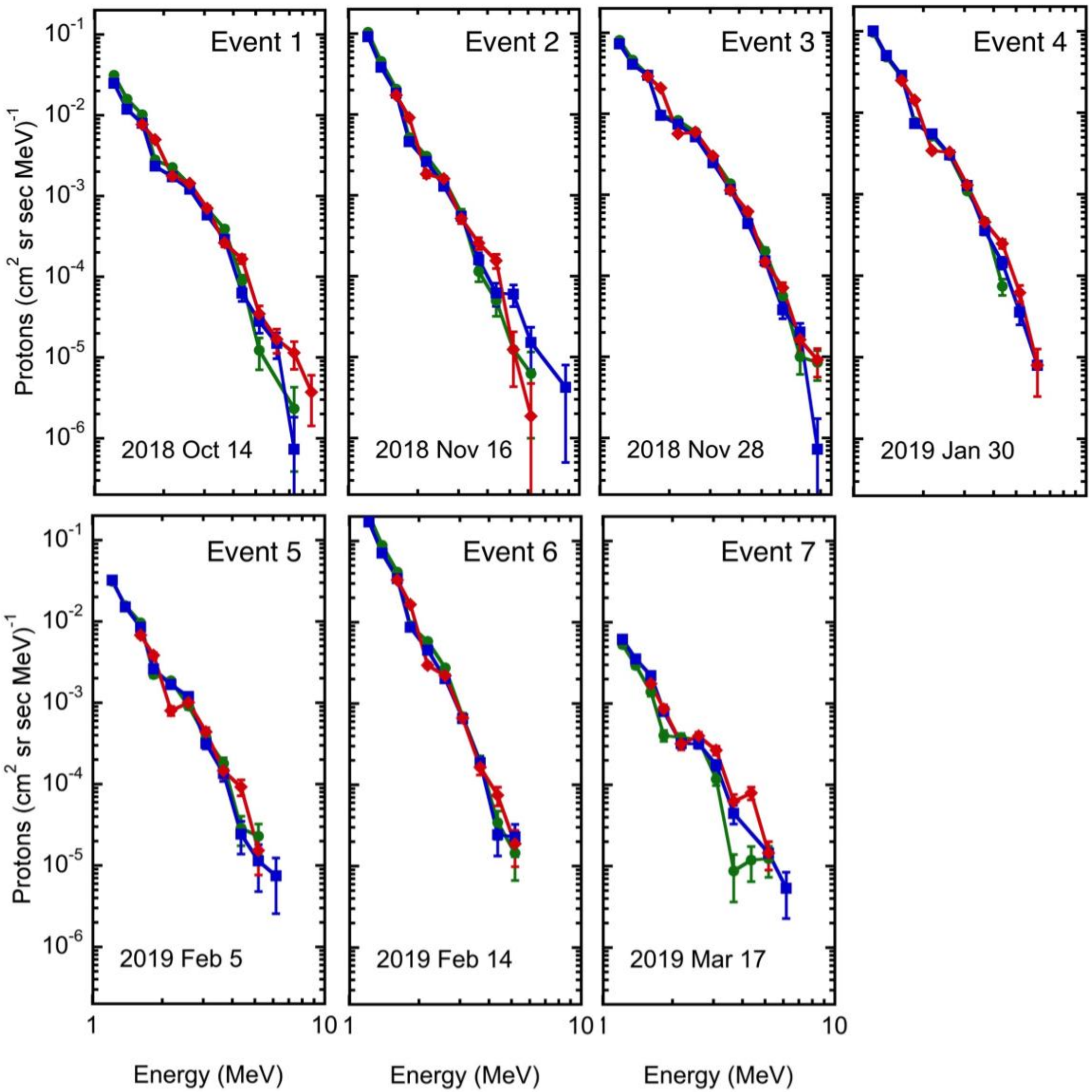
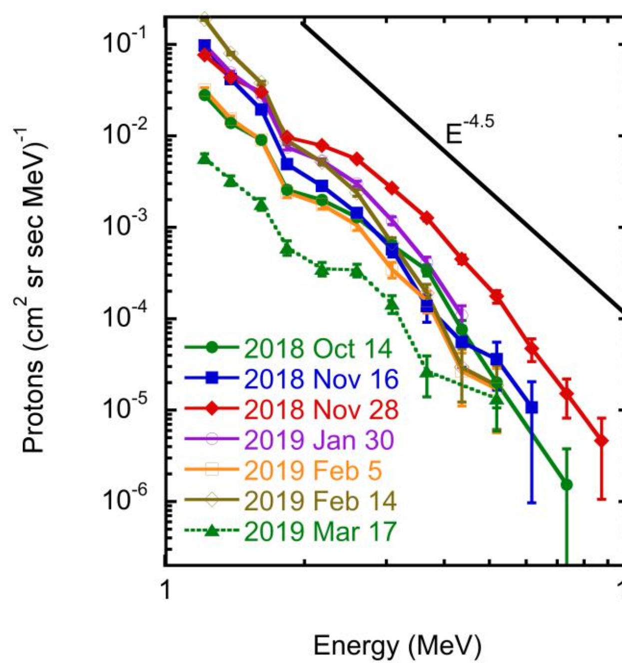
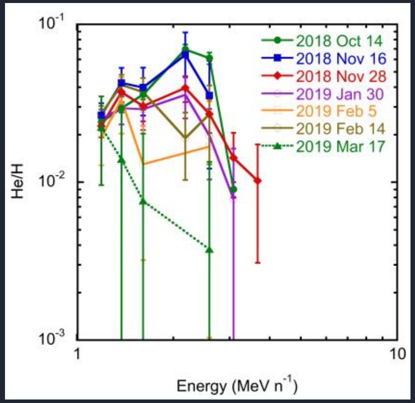
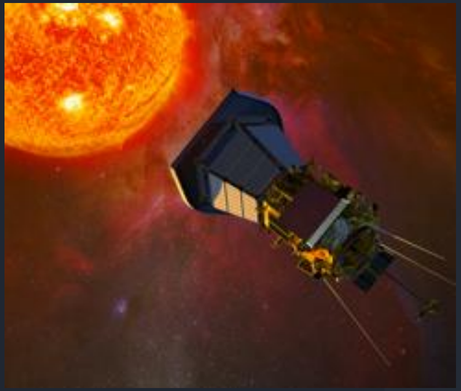



- Time-integrated p$^+$ spectra for each event from **LETA** (green circles), **LETB** (blue circles), and **LETC** (red diamonds)
- **All 3 apertures show agreement** → fairly isotropic particles distributions
- Spectra with **power laws** -4.3 to -6.5



# *PSP Orbits 1,2:* Energetic Particle Increases Associated with SIRs



## SUMMARY AND CONCLUSIONS

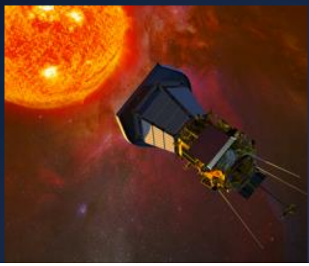
➢ Seven particle SIR increases, two inside 0.5 AU

✓ Softer spectrum ($E^{-4.3}$ to $E^{-6.5}$) than typical for 1 AU (Richardson, 2004)
Whether because of transport or acceleration conditions is not clear

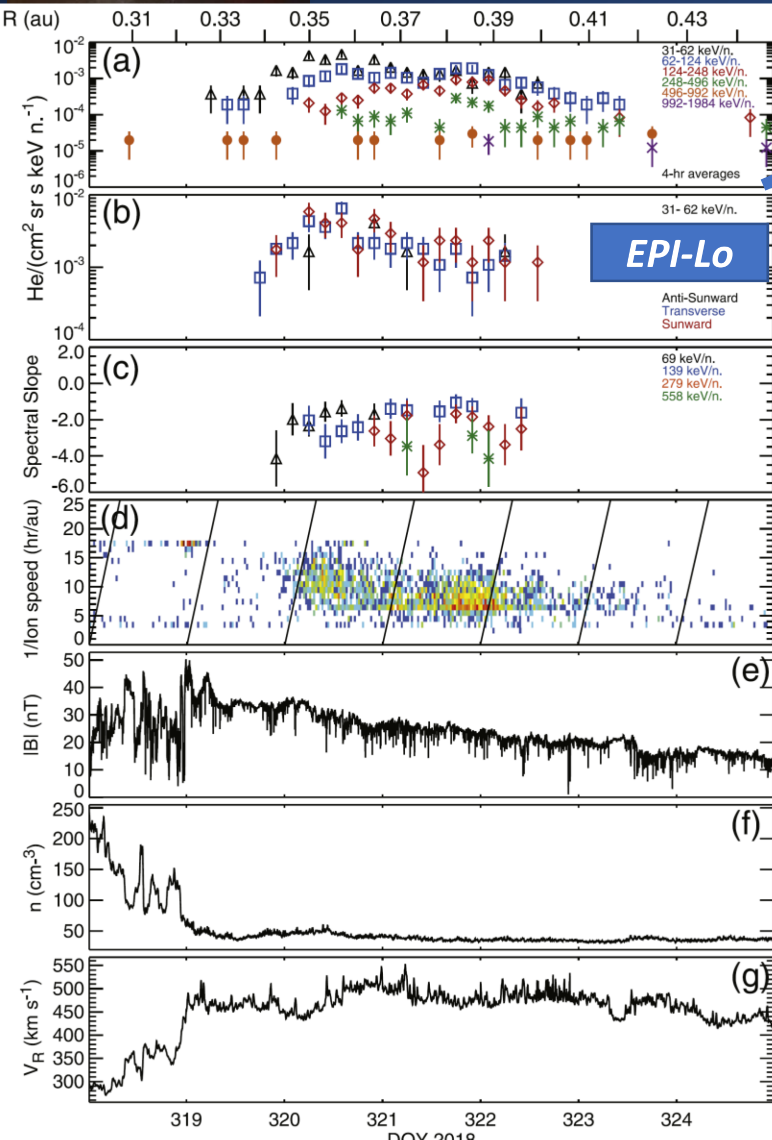
✓ Isotropic, lack of clear Velocity Dispersion, none occurred near a shock/compression region
Suggests events not a result of local acceleration PSP moving through populated flux tube

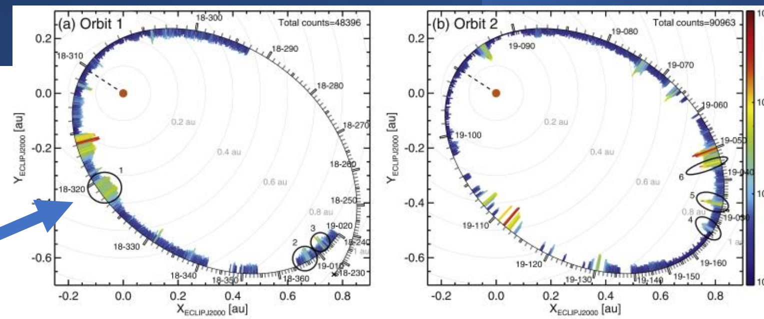
✓ He/H @ 1-2 MeV/n 0.016-0.031
Higher than SEP values
Lower than average 1 AU CIR value except for average of CIRs with v ≤ 600 km/s

**Cohen et al. 2020, *ApJS***



# *PSP Orbits 1,2:* Properties of Suprathermal-through-energetic He Ions Associated with SIRs



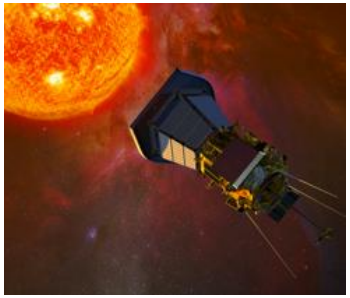




**6 distinct > 0.03 MeV/nuc He enhancements**

- ➢ Event #1: 2018, DOY 318-325, PSP@~0.35 AU
- ➢ (a): 4h av. of 0.03-1.99 MeV/nuc He intensities
  (b) 4h av. Of 0.031-0.062 MeV/nuc He intensities in Anti-SW, Transverse (T) and SW directions
  (c) Spectral slopes γ
  (d) 1/ion speed spectrogram vs. time
  (e)-(g) 10min av. of Bmag, 1min av. n and V
- ➢ Steady decline in Bmag & stable, low n throughout → PSP remained inside the rarefaction region during a high speed stream (~500 km/s) (Allen et al. 2020 *ApJS*)
- ➢ Intensities of 31-62 keV/nuc He ions SW (peak) slightly > than those flowing in the Anti-SW and T directions
- ➢ Inverse VD effect

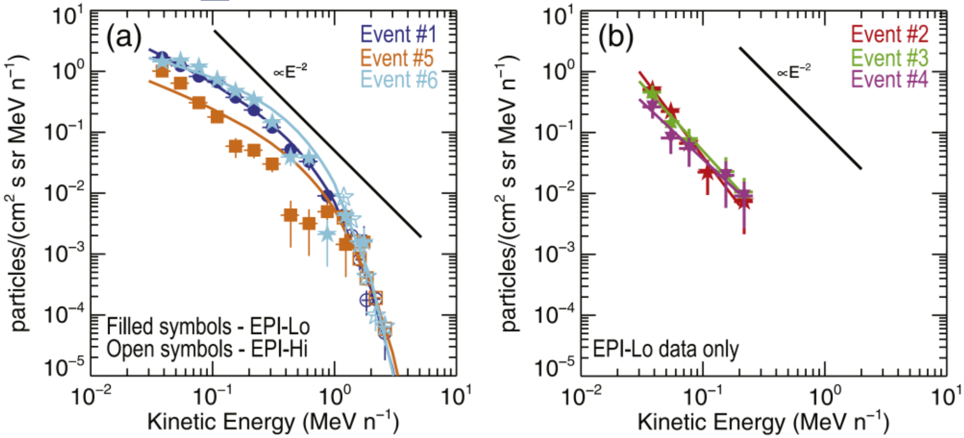
**Desai,..,Malandraki et al. 2020, *ApJS***

# *PSP Orbits 1,2:* Properties of Suprathermal-through-energetic He Ions Associated with SIRs

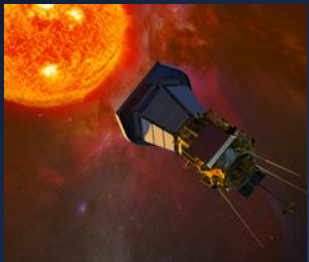


## SUMMARY AND CONCLUSIONS

- **First-ever measurements** of suprathermal-through-energetic **He ions in 0.03-2 MeV/nuc** during CIR/SIR at ~**0.35 AU**!
- Examined time histories of the $J_{diff}$, spectral slopes & anisotropies in **3 different flow directions** (SW, T & Anti-SW)
- **Omni-directional** event-averaged He differential energy spectra. Fit including the 3 events > 1 MeV/nuc by EPI-Hi (*Cohen et al. 2020 ApJS*)
- The **0.03-3 MeV/nuc He energy spectra** associated with SIRs for events #1 and #6 at **0.35** and **0.85 AU** are **identical** (flat power laws modulated by exponential rollovers)

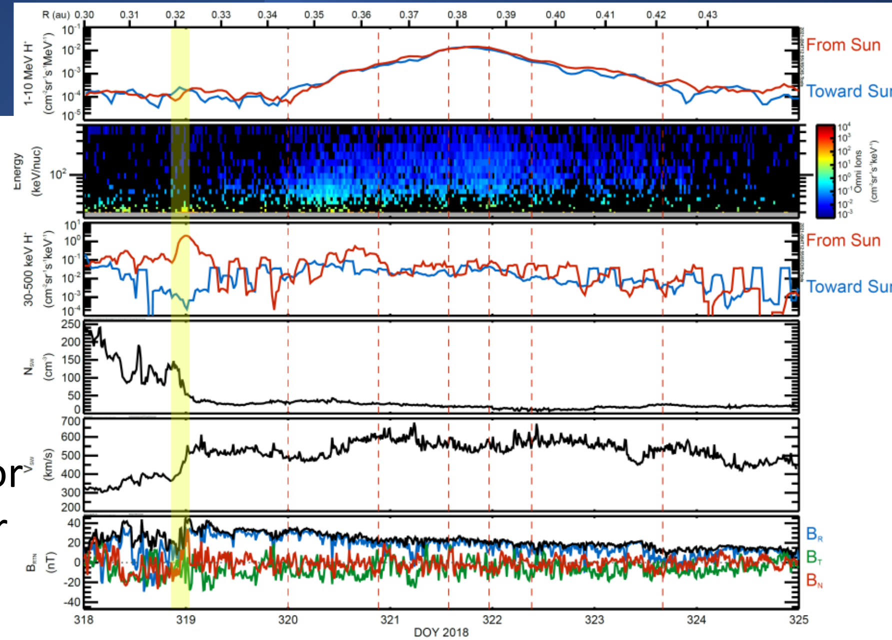



- Evidence that suprathermal He ions in 6 CIR/SIR events by ISΘIS **originate from sources or shocks beyond the location of PSP** (not from local acceleration processes)
- PSP observations pose **a serious challenge for current particle transport models** that predict turnovers in the energy spectra at lower energies below ~0.5 MeV/nuc due to adiabatic energy losses

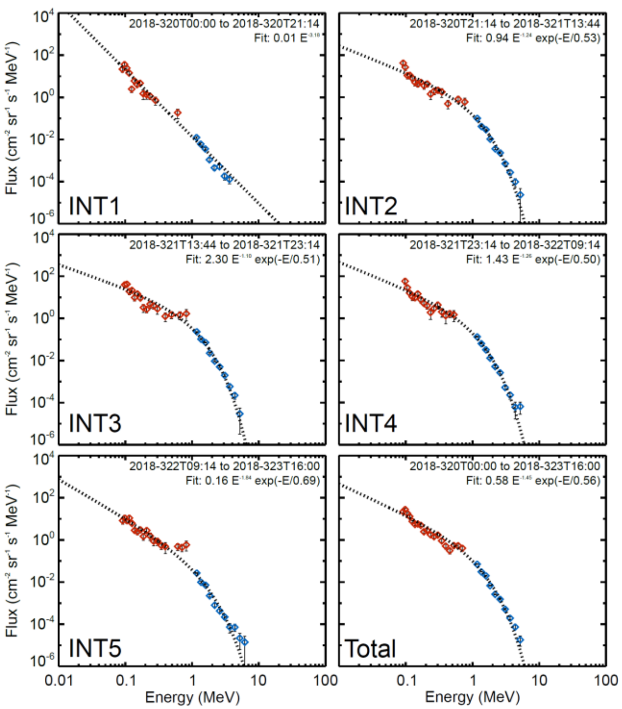


# Time evolution of SIR Energetic Particle Spectra in the Inner Heliosphere

Joyce et al. 2021, A&A




- DOY 320-324, 2018 proton enhancement event by PSP @0.34 AU: SIR event related to the compression region on DOY 319 (McComas et al. 2019; Cohen et al. 2020; Desai et al. 2020-Event #1)

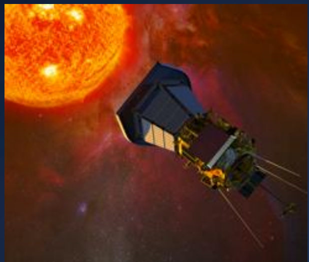



Proton spectrum measured by ISOIS for each interval, and for the entire interval

- Desai et al. 2020 routine for PROTON spectra fit. INT1: simple power law (**$j=j_oE^{-\gamma}$**) INTx: **$j=j_oE^{-\gamma}\exp(-E/E_o)$**

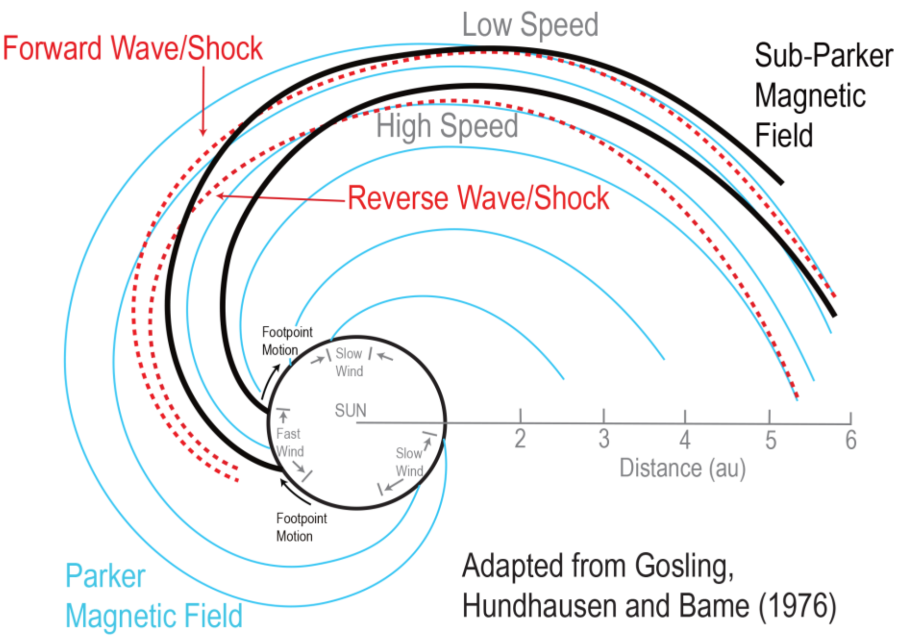
- Spectrum **~const.** after the 1st day → Modulation of EPs during transport much weaker than predicted by Fisk and Lee (1980). Distance to the source region should be increasing → **increasing transport effects on the particles expected**. ~Const. spectrum of low-energy particles INT 2, 3, & 4 (most affected by modulation)

<u>**Conclusion:**</u> **Potential importance of acceleration at pre-shock compression regions closer to the Sun, with a broad source region. Closer PSP connection due to the sub-Parker spiral structure of B**

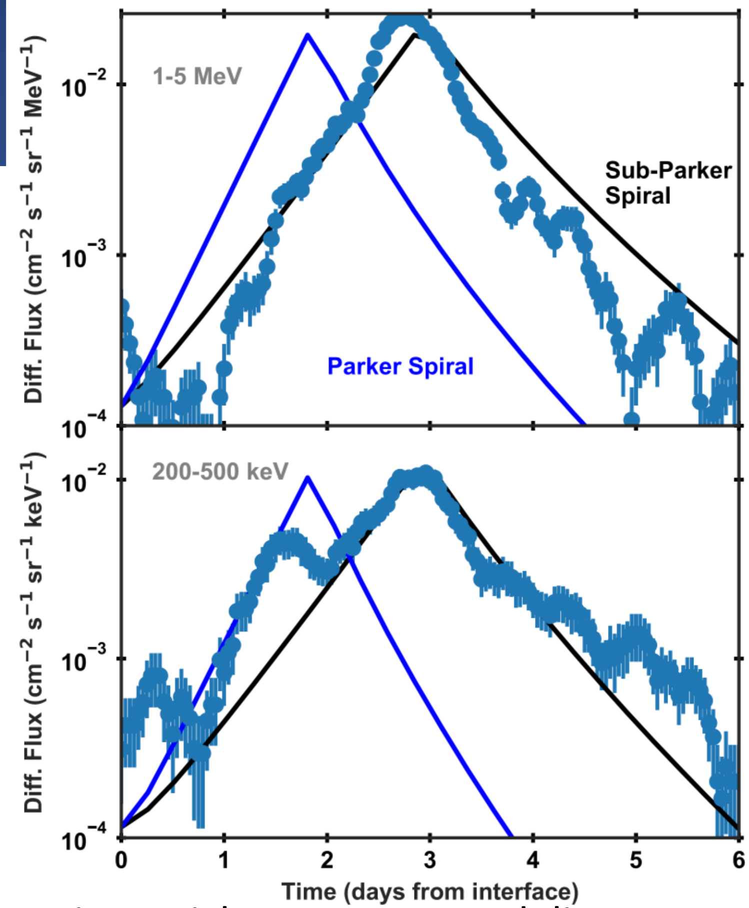


# A New View of Energetic Particles from SIRs Observed by PSP

Schwadron,…,Malandraki et al. 2021, *A&A*




- Illustration of the IMF structure in an SIR (adapted)




<u>Energetic particle transport modeling</u>

Comparison of **observed (Blue data points)**, modeled $J_{diff}$ (curves) at higher and lower energies. Modeled EPs accelerated at the SIR Reverse compression or shock and propagate back to PSP along **Sub-Parker (black curves)** and **Parker field lines (blue curves)**

- **<u>Schwadron & McComas 2005, 2021; Schwadron et al. 2005; Murphy et al. 2002:</u>** With footpoint motion at the Sun, IMF lines (black) connected between fast & slow sw and form the Sub-Parker spiral in rarefaction regions where the fast sw stretches out B lines in the radial direction

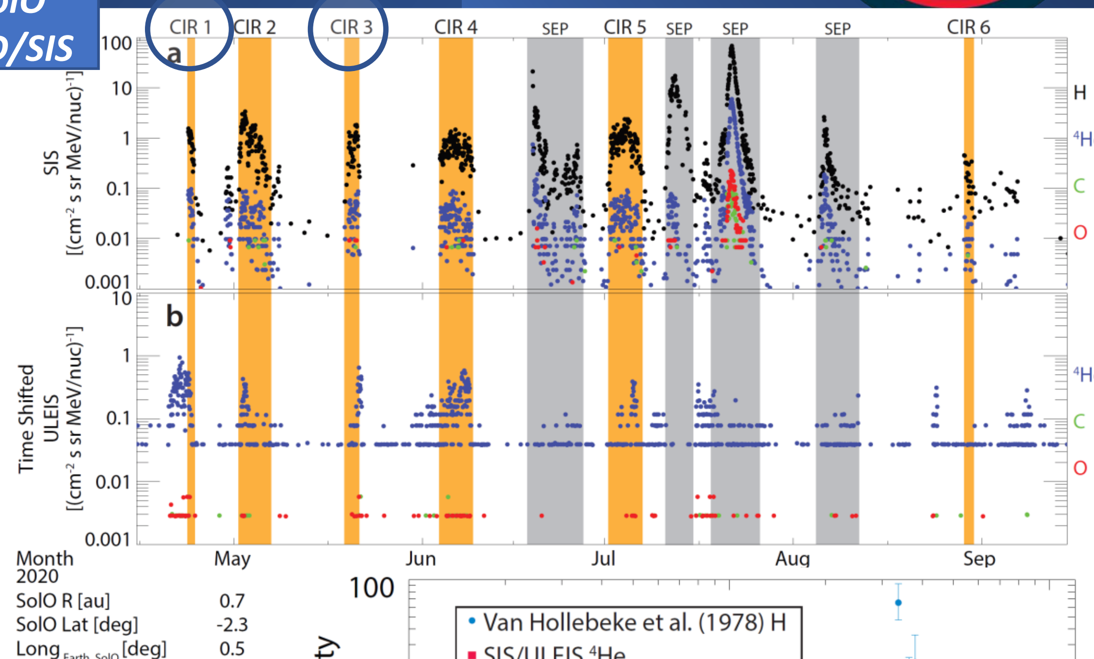
# Suprathermal Particles from CIRs during the First Perihelion of Solar Orbiter

Allen et al. 2020, *A&A*

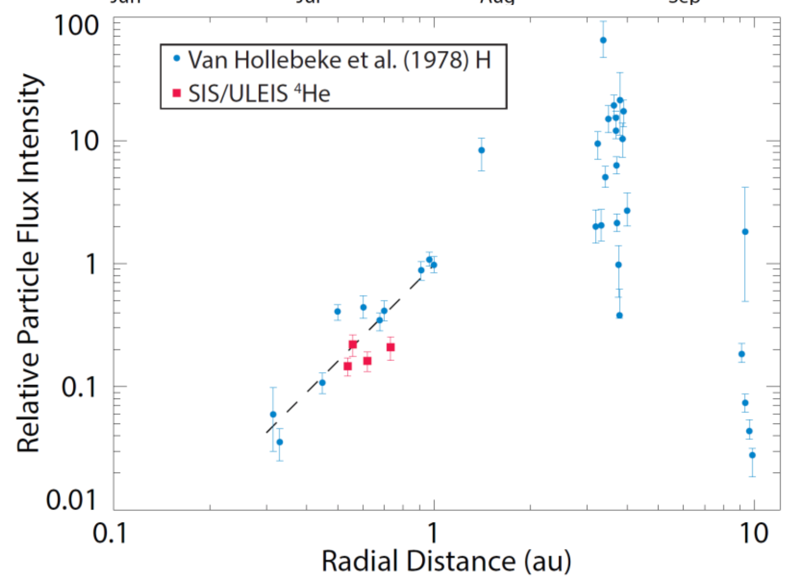
***SolO EPD/SIS***

- Overview of 226-320 keV/nuc ions (H, $^4$He, C, O) from 2020 Apr 15-Sept 15 by SolO/EPD/SIS and ACE/ULEIS. 6 CIR-associated suprathermal particle event seen (**Orange**). CIR events 1-5 observed by both SIS and ULEIS

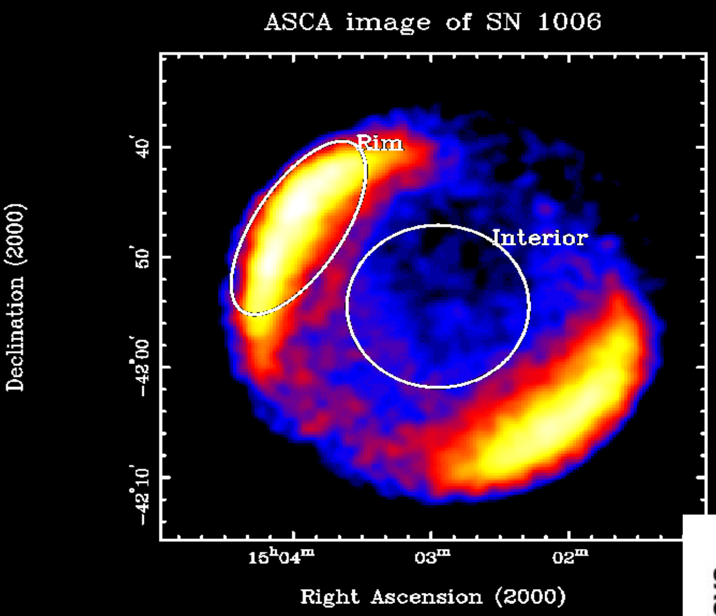
- $^4$He spectra from **ACE** and **SolO** show **good agreement**. Turnover in the low energies as predicted by F&L (1980) **not observed**



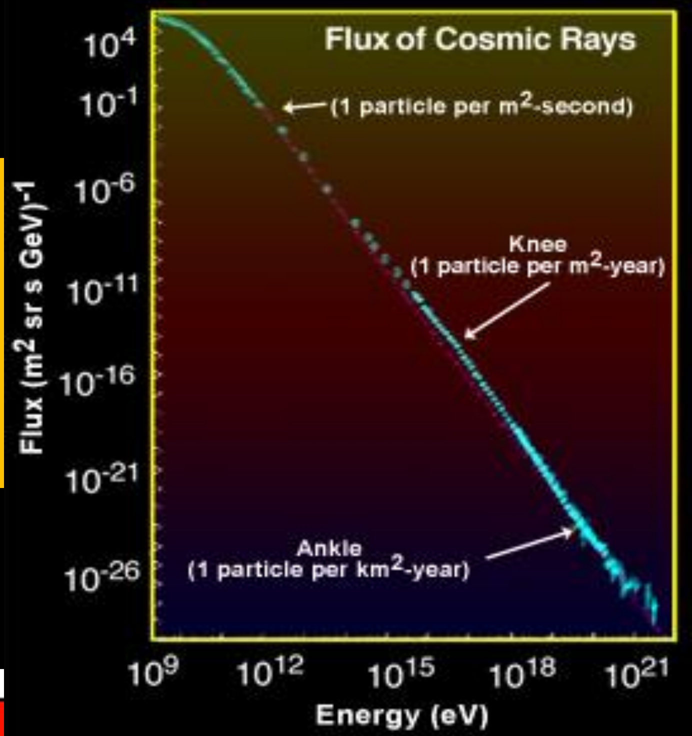

- **Radial gradients in the $^4$He intensities between SIS and ULEIS very similar to those found for more energetic H between Helios 1 and 2 and IMP 7 (Van Hollebeke et al. 1978)**



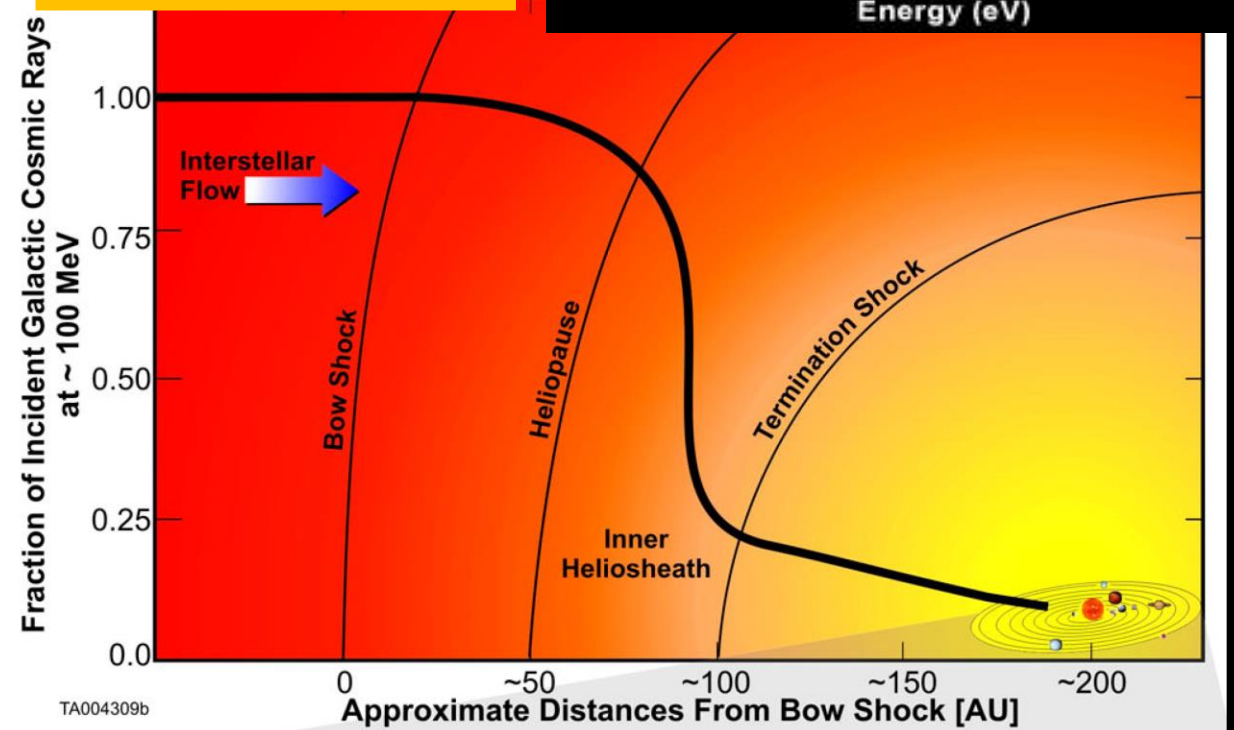
# Galactic Cosmic Rays




GCR energy spectrum is a power-law in log-log space




***Schwadron et al. Space Sci. Rev., 2017***



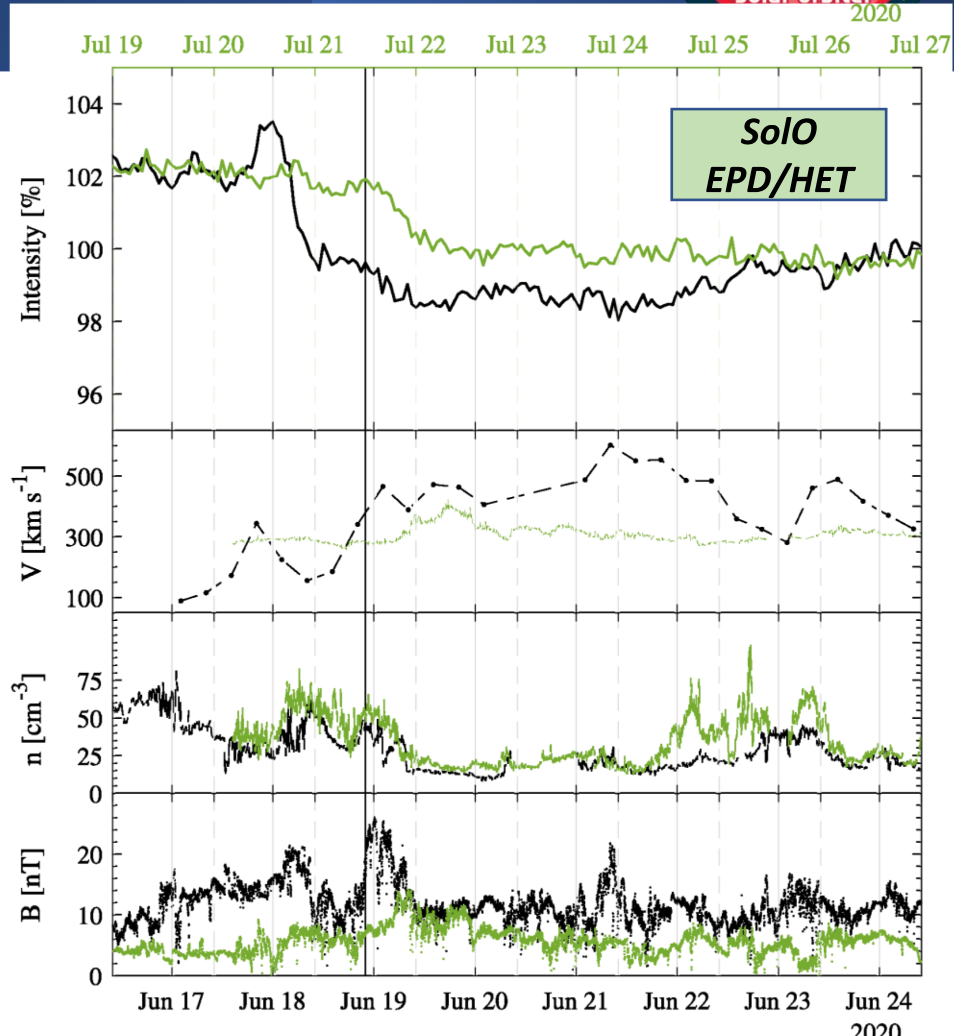

- Produced during supernovae explosions that create relativistic shocks
- GCRs are modulated (fluxes are reduced) in the heliosheath

*Image credit: G. P. Zank*

# First identification of a recurrent Forbush Decrease at Solar Orbiter

Aran,…,Malandraki et al. 2021, *A&A*

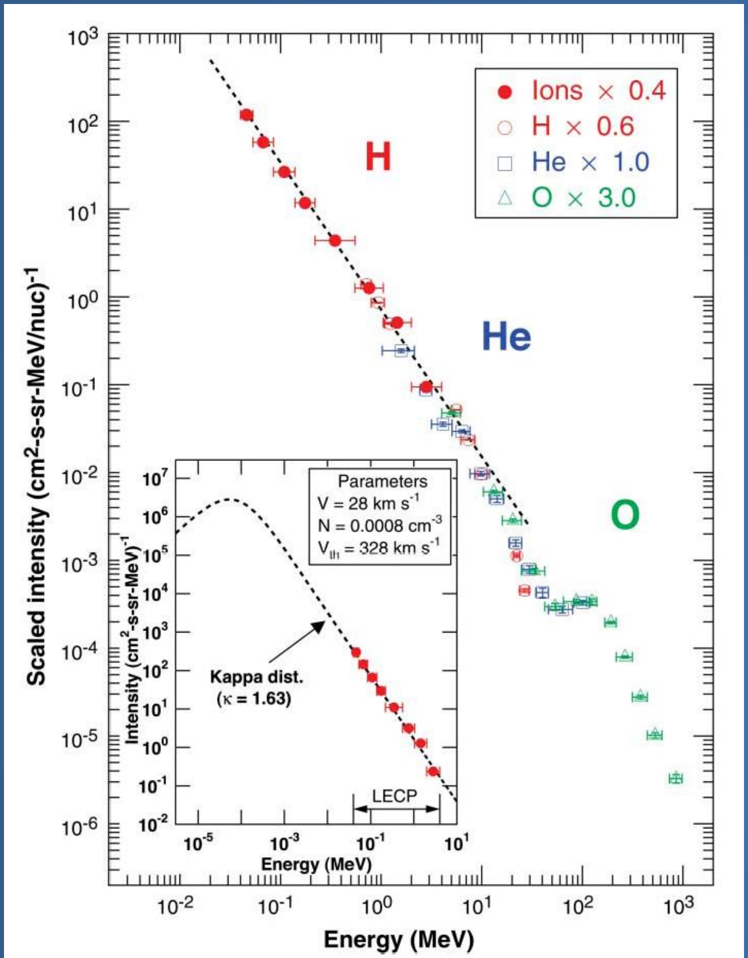
- GCR intensity (as measured by the > 17-20 MeV count rates of the **EPD/HET** detector) from 17-24 June 2020
- Initial short-term GCR intensity increase and 2 consecutive decreases. 1st: 00:00 UT on Jun 18 (~4% hourly percentage variation, 2nd: 22:00 UT on Jun 18 (solid vertical line) (~2% variation)
- Two-step Forbush decrease, **what is the driver of the GCR decreases?**
- **B** increase @ 22:00 UT on Jun 18, increase of the sw speed & decrease in density → **A High Speed Stream (HSS) swept over SolO**
- **Observations show that the GCR decrease at 1200 UT on Jul 21 in good agreement with the estimated recurrence time for the HSS (green trace)**

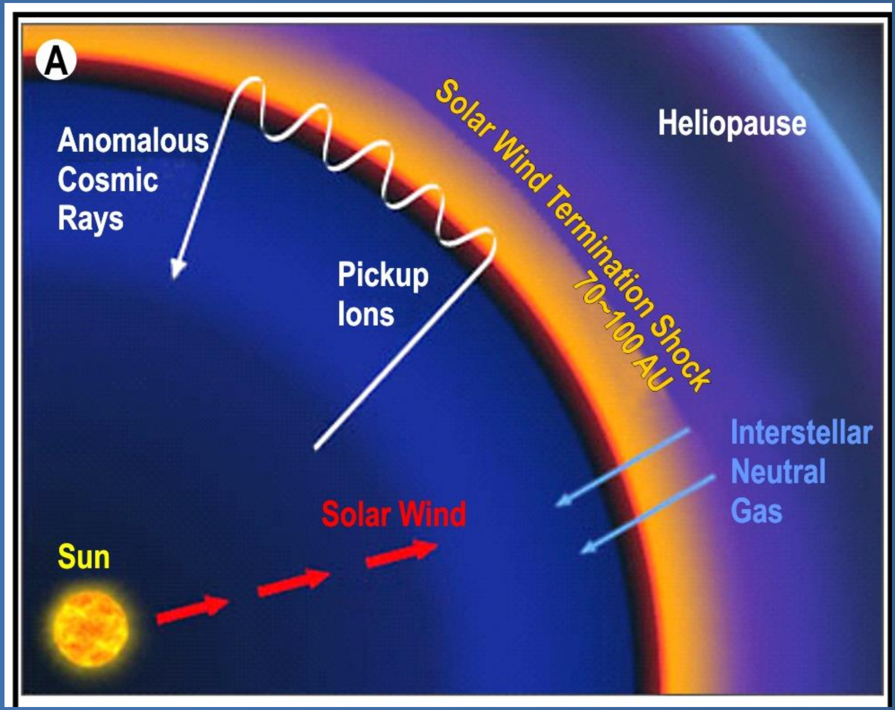



- Recurrence of this CIR in previous solar rotations ~coincides with CIR 1 and CIR3 of Allen et al. 2020

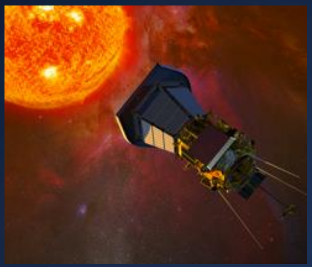
**Freiherr von Forstner et al. 2021, *A&A:*** FD by SolO (Apr 2020)

# Anomalous Cosmic Rays



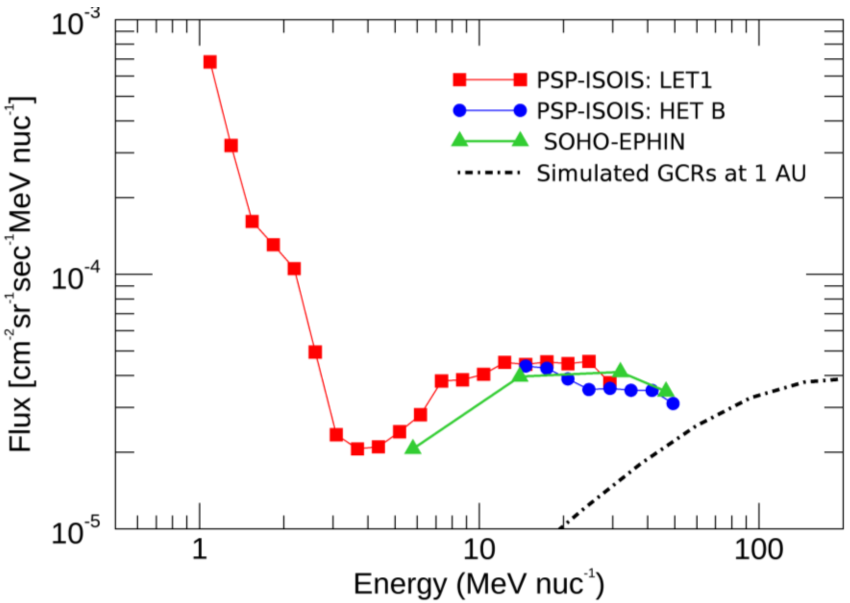

- Interstellar neutrals are ionized, and get convected ("picked-up") to the termination shock by the solar wind
- En-route they get accelerated by shocks, turbulence etc.
- At the termination shock, they get accelerated to 100s of MeV
- Propagate back into the inner solar system, measured near Earth

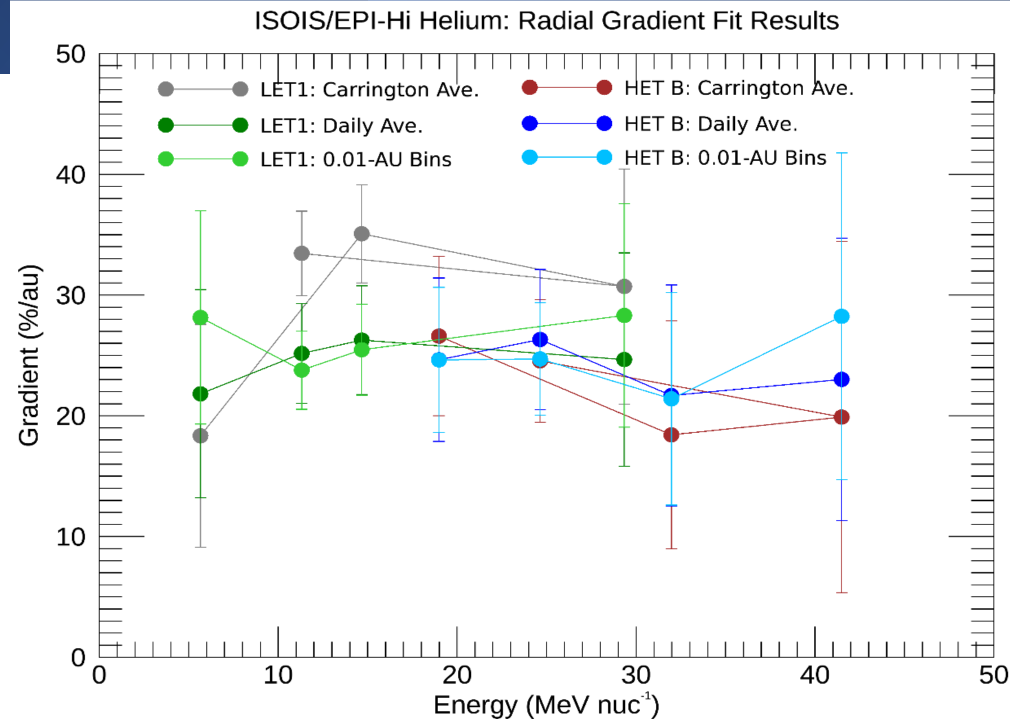


# First Observations of Anomalous Cosmic Rays in to 36 Solar Radii

**Rankin et al. 2021, *ApJ***

## Event-Subtracted Helium Fluxes (Orbits 1-3)



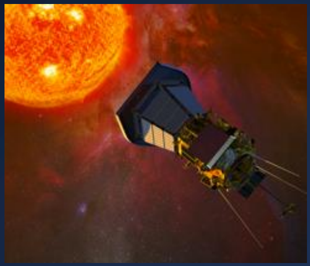




- Very low levels of solar activity in the SC 24-25 min → perfect for measuring ACRs and GCRs!
- Examine radial trends in ~5 to 50 MeV/nuc, ISOIS/EPI-Hi Helium (PSP Orbits 1-3)
- Event-Subtracted Helium Fluxes following de-coupling of the signal from other variations (e.g. SEP events, modulation by sw streams etc)

- 3 types of Fits

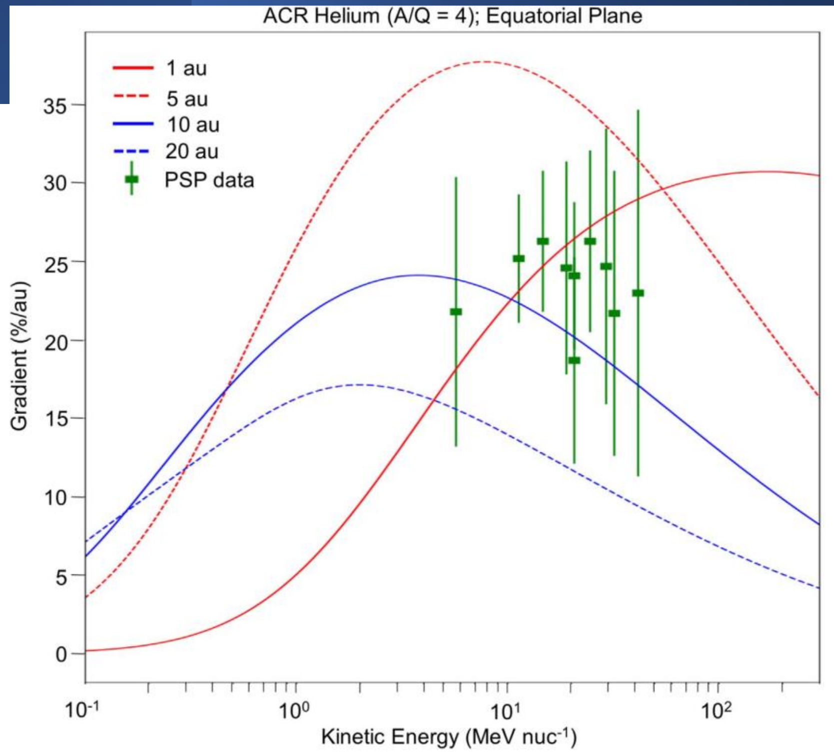
1) Carrington Longitude Averages
2) Daily Averages
3) Radially-Binned

# First Observations of Anomalous Cosmic Rays in to 36 Solar Radii



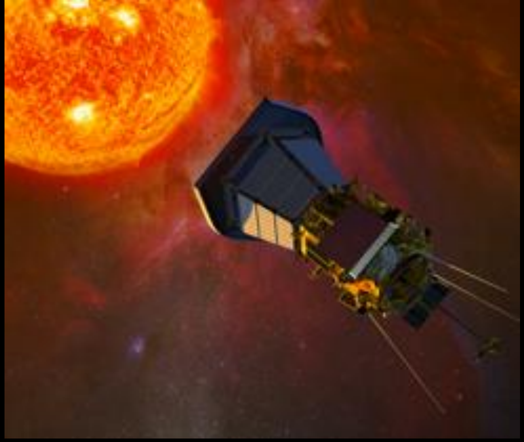
Rankin et al. 2021, *ApJ*

- Simulation of ACR Oxygen gradients: Strauss & Potgieter (2010) with minor updates and modifications
- Applicability inside 1 AU yet to be determined
- Challenges for current models
  - Lack of observations: Low-energy measurements (ACRs & GCRs), In the ecliptic, Near the Sun, Over the Solar Cycle
  - No clear way to treat the inner boundary condition
    - Reflecting at 1 AU → zero radial gradient
    - Anisotropy near the Sun could invalidate Parker Transport




## CONCLUSIONS & TAKEAWAYS

- ➢ Strong signatures of a radial gradient in ACR He (PSP)
  - 25 ± 5 %/AU → 34 ± 6 %/AU with GCRs subtracted
  - ~1.0 to ~0.17 AU (PSP orbits 1-3)
  - Currently a qA > 0 cycle (smaller gradients expected than in qA < 0)
  - Our signature is much stronger than all prior He measurements (typically ~10 to 15%/au)
- ➢ First measurements of radial intensity gradients since ~2010
  - Both *Voyagers* have crossed the heliopause
  - *IBEX* has taken a whole solar cycle of observations
- ➢ Measurements are critical to refining solar modulation models!



## Golden age of Solar & Heliospheric Physics

- Both SolO and PSP will make in-situ measurements of the solar wind plasma, fields, waves, and suprathermal and energetic particles between ~10 $R_S$ and Earth orbit, simultaneously with high-resolution imaging and spectroscopic observations of the SEP source regions on the Sun from multiple vantage points

- The next years promise to revolutionize our understanding of SEP acceleration and transport by exploration of the solar corona and inner heliosphere with the state-of-the-art sensors on board of these ongoing missions!

# Origin and Transport of Energetic Particles

## Leads:

**Olga Malandraki,** *National Observatory of Athens, Greece*

**Vratislav Krupar,** *NASA Goddard Space Flight Center, USA*

**Solar Orbiter In-Situ**

**Working Group**

**> 130 members**

## Objectives:

- Improvement of our understanding of the origin and transport of energetic particles in the heliosphere, in association with Coronal Mass Ejections (CMEs) and Corotating Interaction Regions (CIRs) propagation and evolution
- How and where are energetic particles injected at the sources and in particular what are the seed populations for energetic particles?
- How are energetic particles released from their sources and distributed in space and time? (transport radially and across magnetic field lines from the corona in the heliosphere)
- Use of EPD observations to better constrain current particle transport models that describe SEP events – Improvement of existing propagation models;
- Study of the temporal and spatial evolution of energetic particles accelerated by CIRs
- More accurate source identification and timing studies of SEP events - Radio counterparts
- Origin of relativistic ions in Ground Level Enhancement (GLE) events;
- Origin of local particle enhancements in association with coherent structures in the solar wind in the inner heliosphere
- Investigate roles of CME- and SIR-driven interplanetary shocks, solar flares, and other processes in accelerating energetic particles
- Resolve conditions that determine when interplanetary shocks efficiently accelerate energetic particles
- Generation of radio waves throught the interaction of the solar energetic electrons with the ambiant medium (Langmuir wave generation, plasma mode conversion ...)
- Scattering of radio waves by the ambient density fluctuations and turbulence
- Synergy between RPW and ground-based radio observatories

## Google group: solo_iswg_energetic_particles_origin_transport