Energetic Particle Measurements with Solar Orbiter

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Outline

- Solar Orbiter (SO) Mission
- Energetic Particle Detector (EPD) Suite on SO
- Questions that will be addressed by SO/EPD:
  - Acceleration
  - Seed Particle
  - Transport
- SO-SIS instrument and data products
- EPD data

Solar Orbiter Mission

- A joint ESA-NASA mission ~~to be~~ launched in February 2020
- The spacecraft will take a unique combination of measurements: *in situ* measurements will be used alongside remote sensing close to the Sun to relate these measurements back to their source regions and structures on the Sun's surface.
- Solar Orbiter will set about answering four top-level science questions:
  - ***What drives the solar wind and where does the coronal magnetic field originate from?***
  - ***How do solar transients drive heliospheric variability?***
  - ***How do solar eruptions produce energetic particle radiation that fills the heliosphere?***
  - ***How does the solar dynamo work and drive connections between the Sun and the heliosphere?***

Müller et al. (2013)

Mission Design

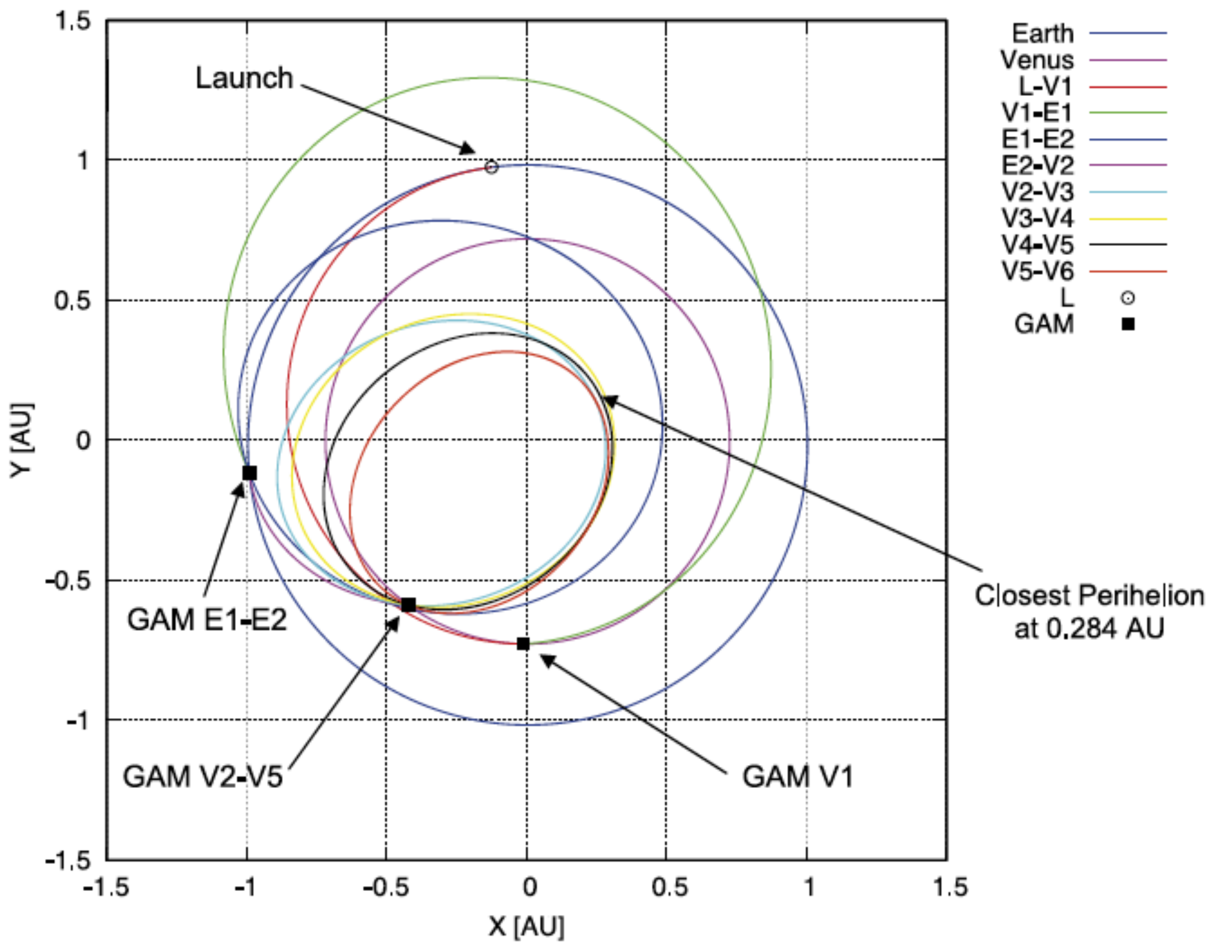
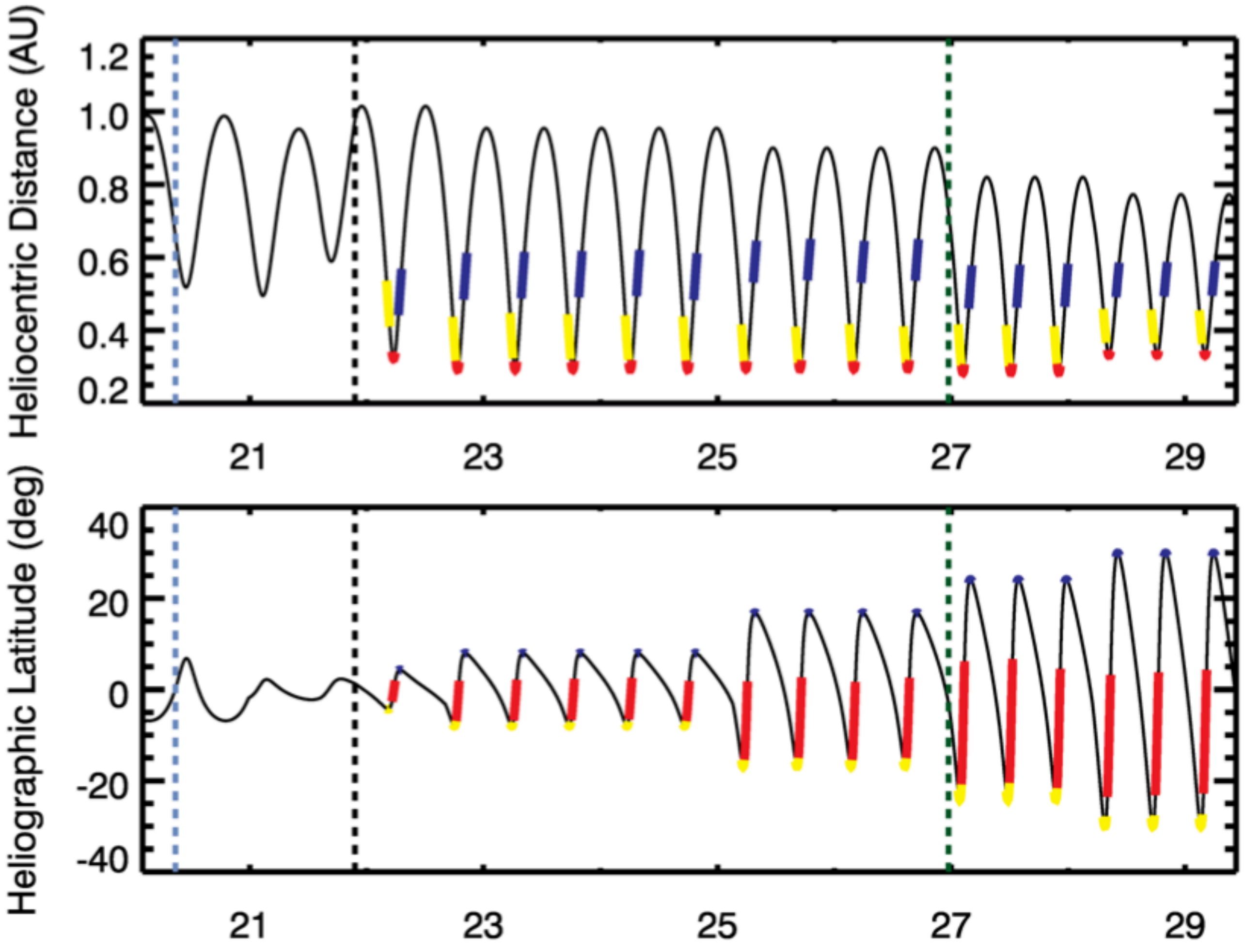


Figure 2 *Solar Orbiter's* trajectory viewed from above the ecliptic (January 2017 launch). The gravity assist maneuvers (GAM) at Earth (E) and Venus (V) are indicated, along with the orbits of these two planets.

- ***NASA-provided launcher***
- ***First perihelion is reached 1.5 years after launch***
- ***Operating orbit has a 168 days period***
- ***Resonant orbit with Venus***
- ***Minimum perihelion at 0.28 AU***
- ***7 years nominal mission at 25° inclination***

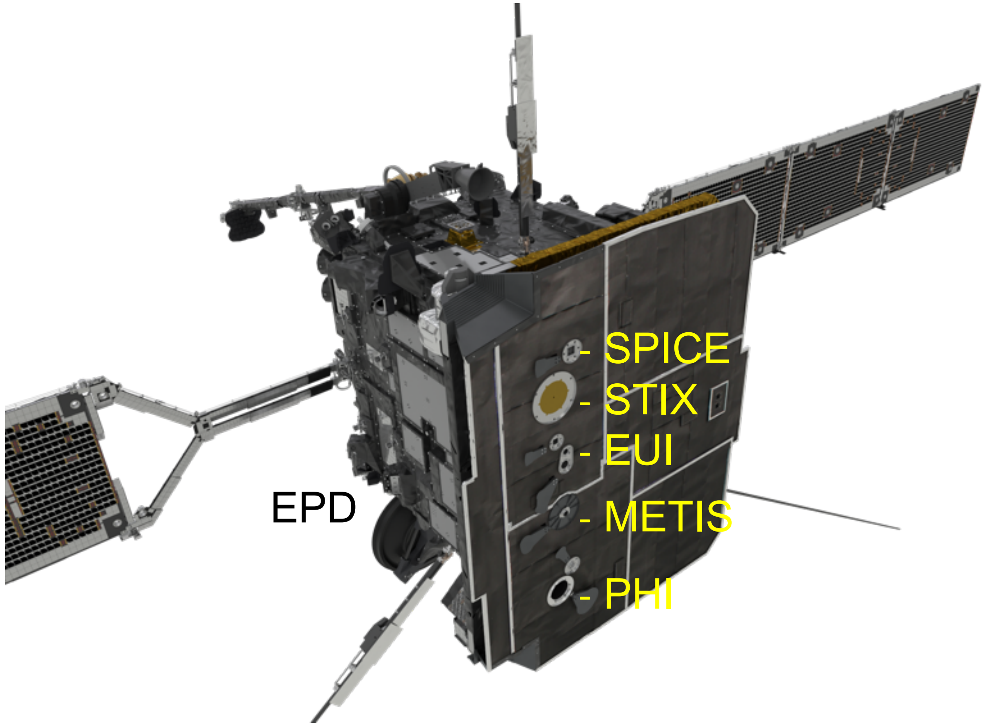
Mission phases (Feb 2020 launch)

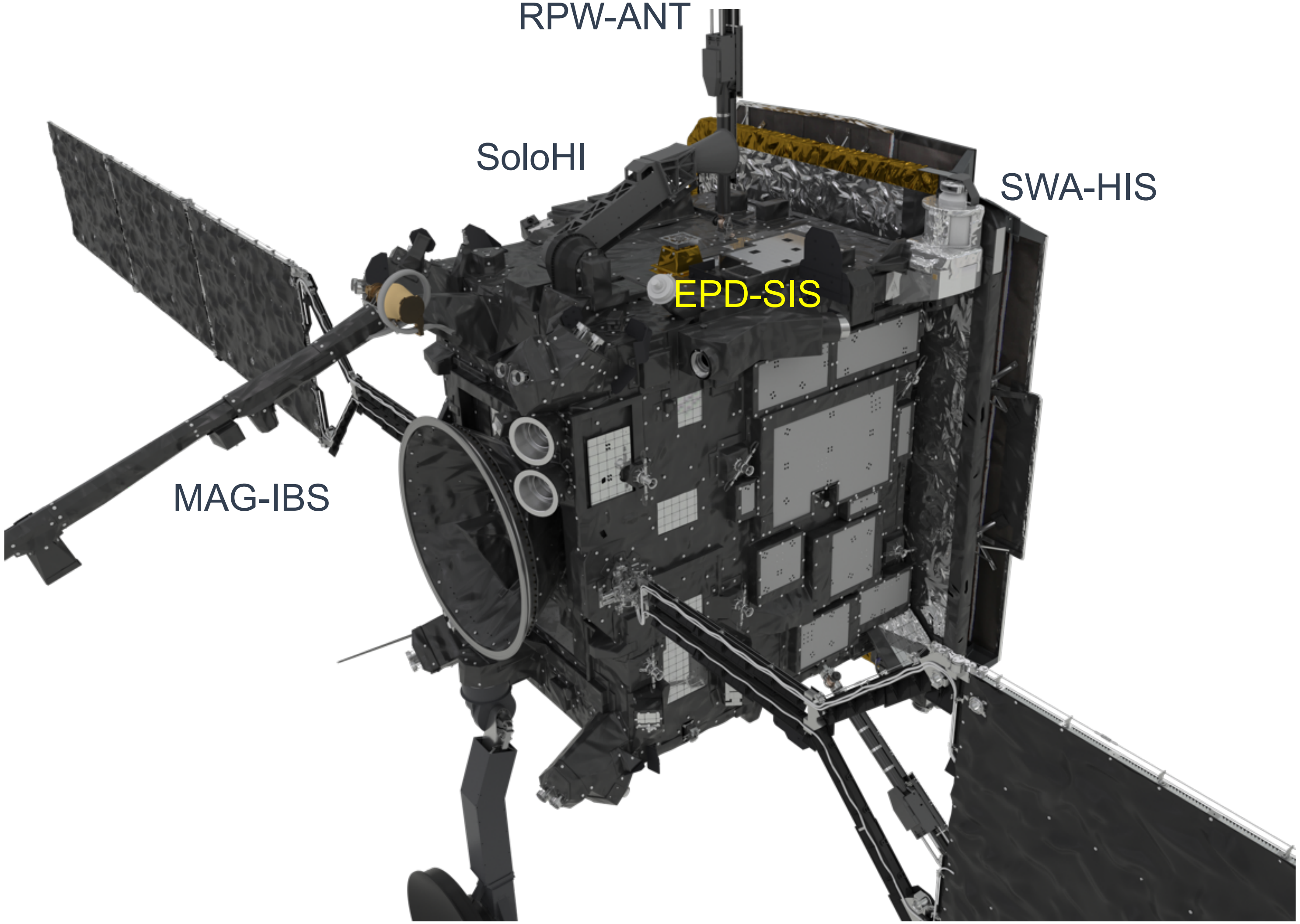
- **CP** Cruise Phase
  - From 97 days after launch until the planetary fly-by that puts the spacecraft into the NMP orbit.
  - Short: 561 days
- **NMP** Nominal Mission Phase.
  - for Feb 2020 launch, this starts in Nov 2021



Solar Orbiter Spacecraft

10 instrument suite: 4 in-situ; 6 remote





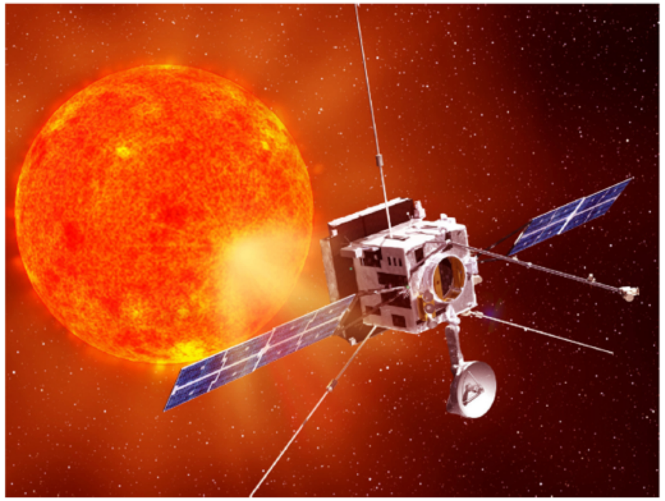
Solar Orbiter: Energetic Particle Science Question

esa

ESA/SRE(2011)14
July 2011

Solar Orbiter

Exploring the Sun-heliosphere connection



Definition Study Report

European Space Agency

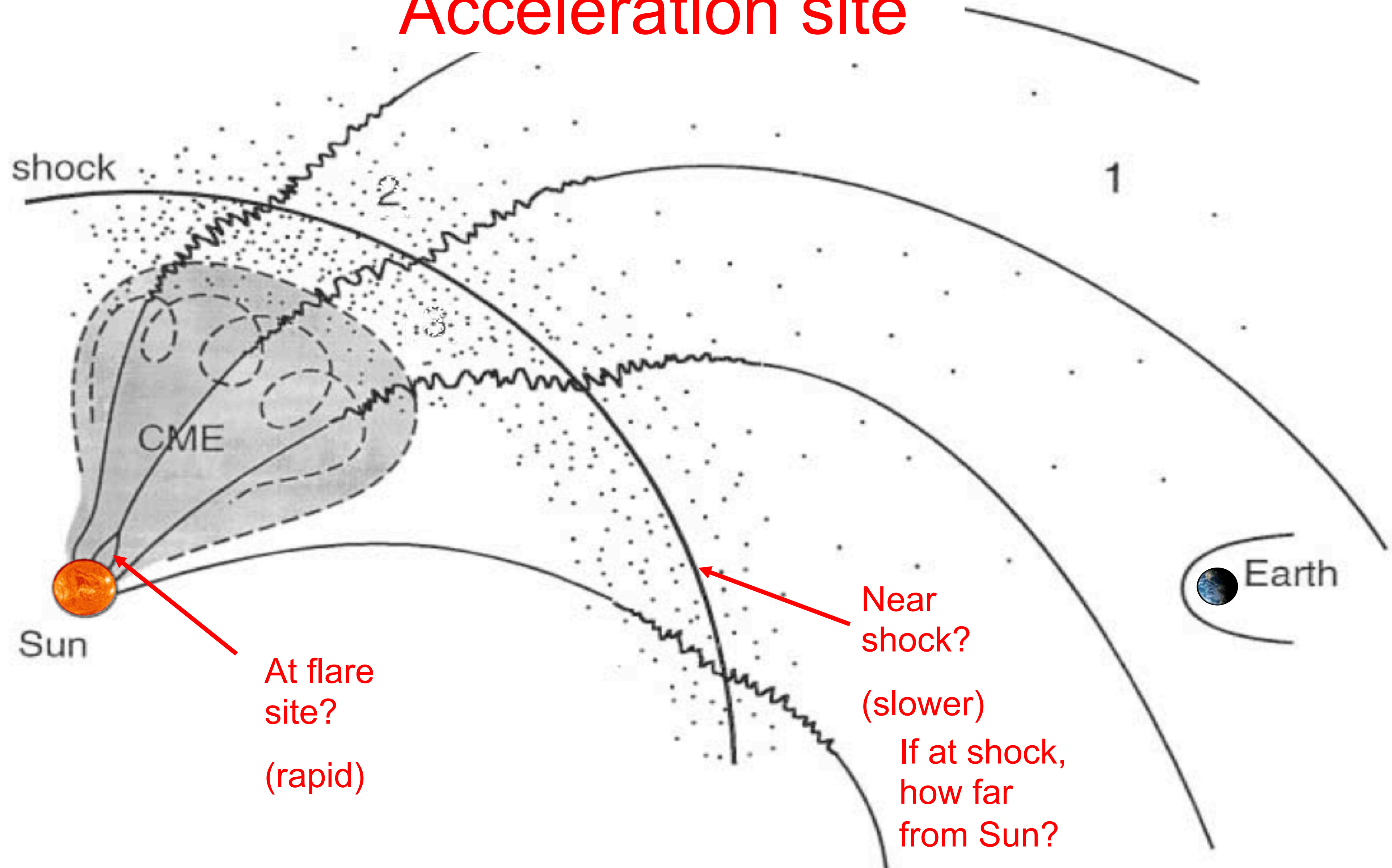
How do solar eruptions produce energetic particle radiation that fills the heliosphere?

1) Acceleration

2) Injection/Seed population

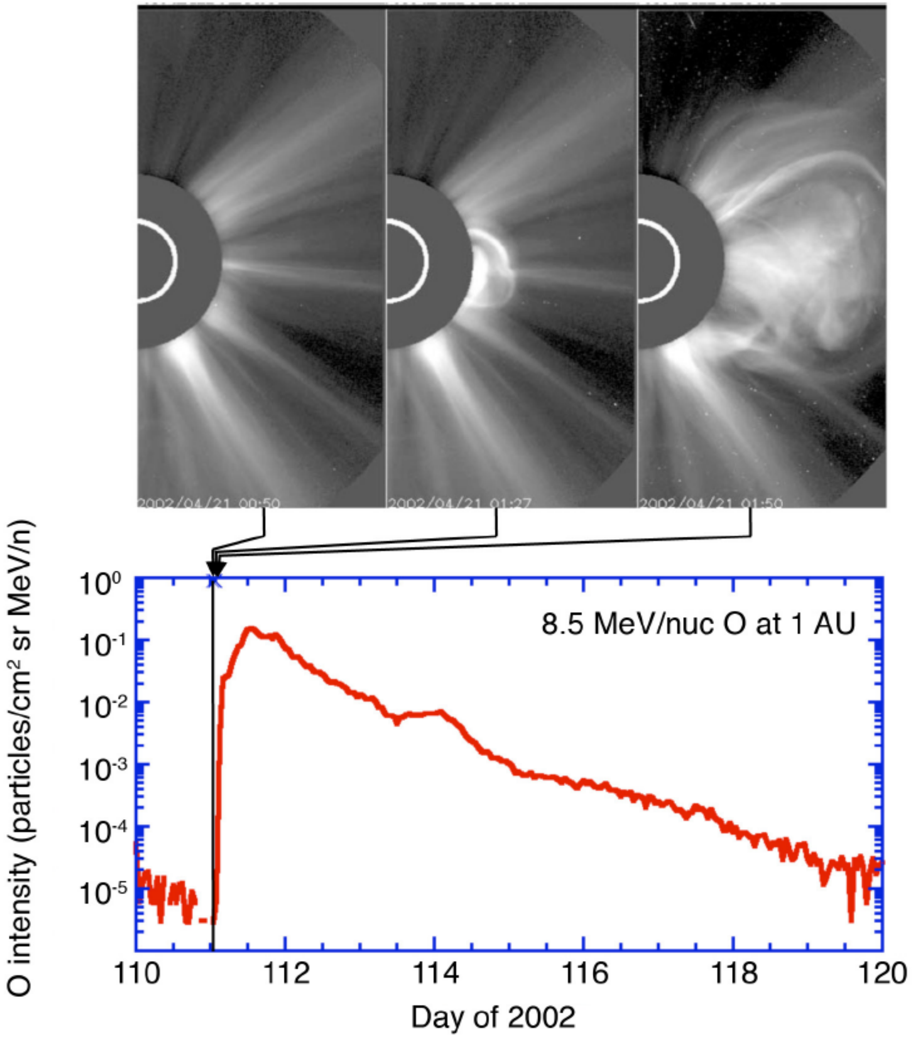
3) Transport

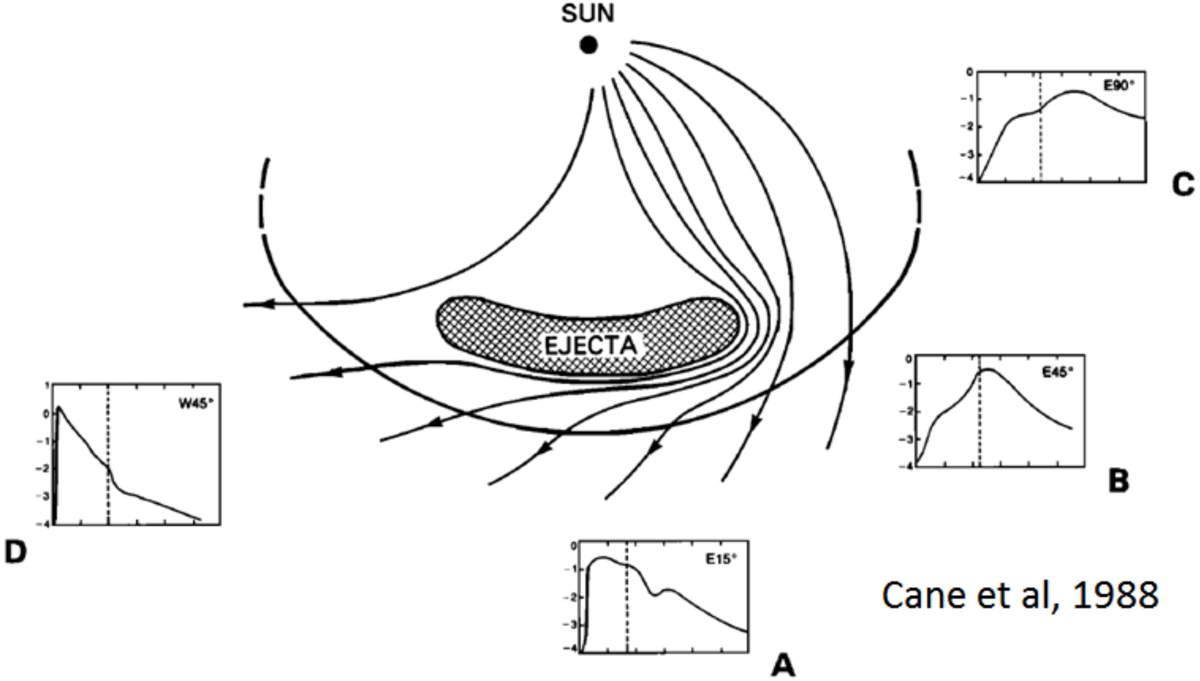
Acceleration site



Adapted from Marty Lee, ApJS, 158, 2005

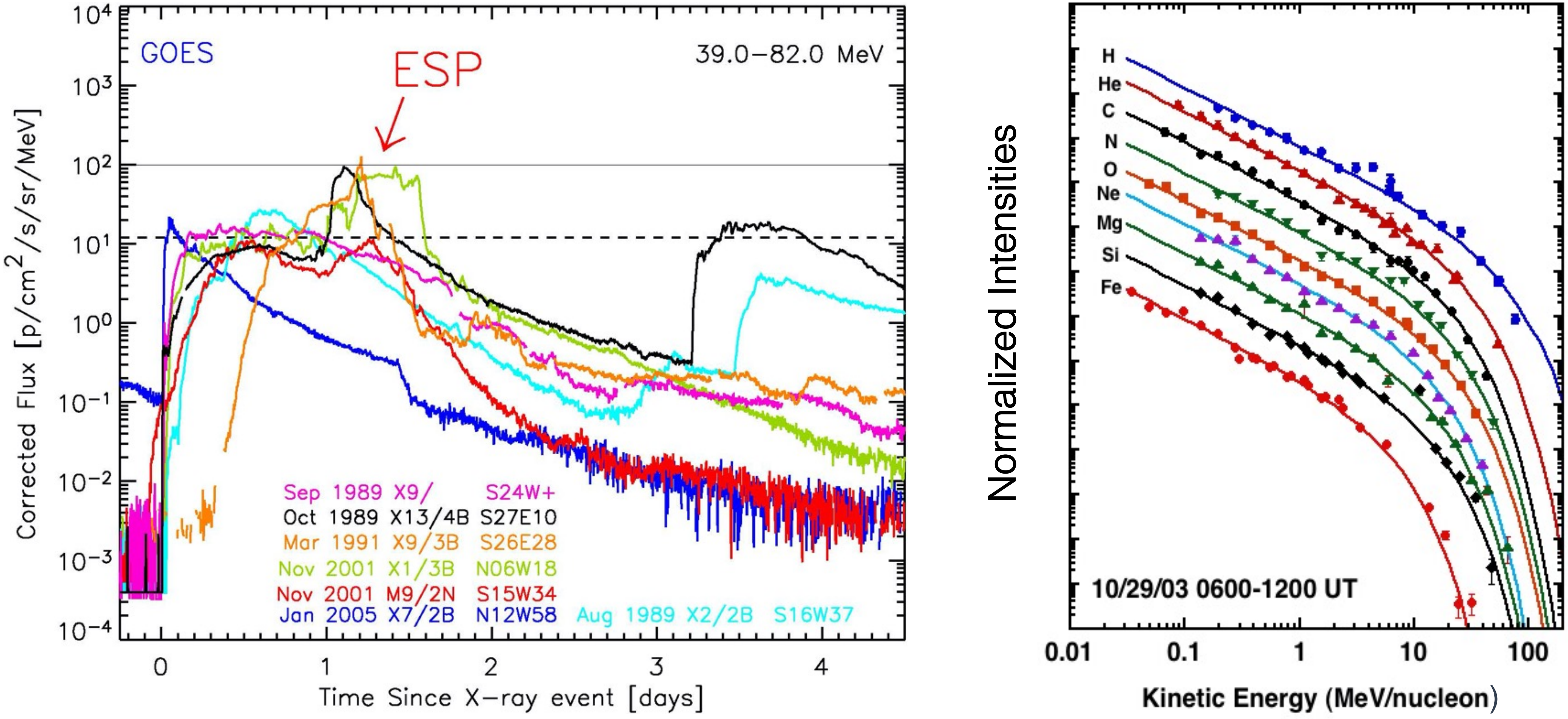
1. Shock Acceleration





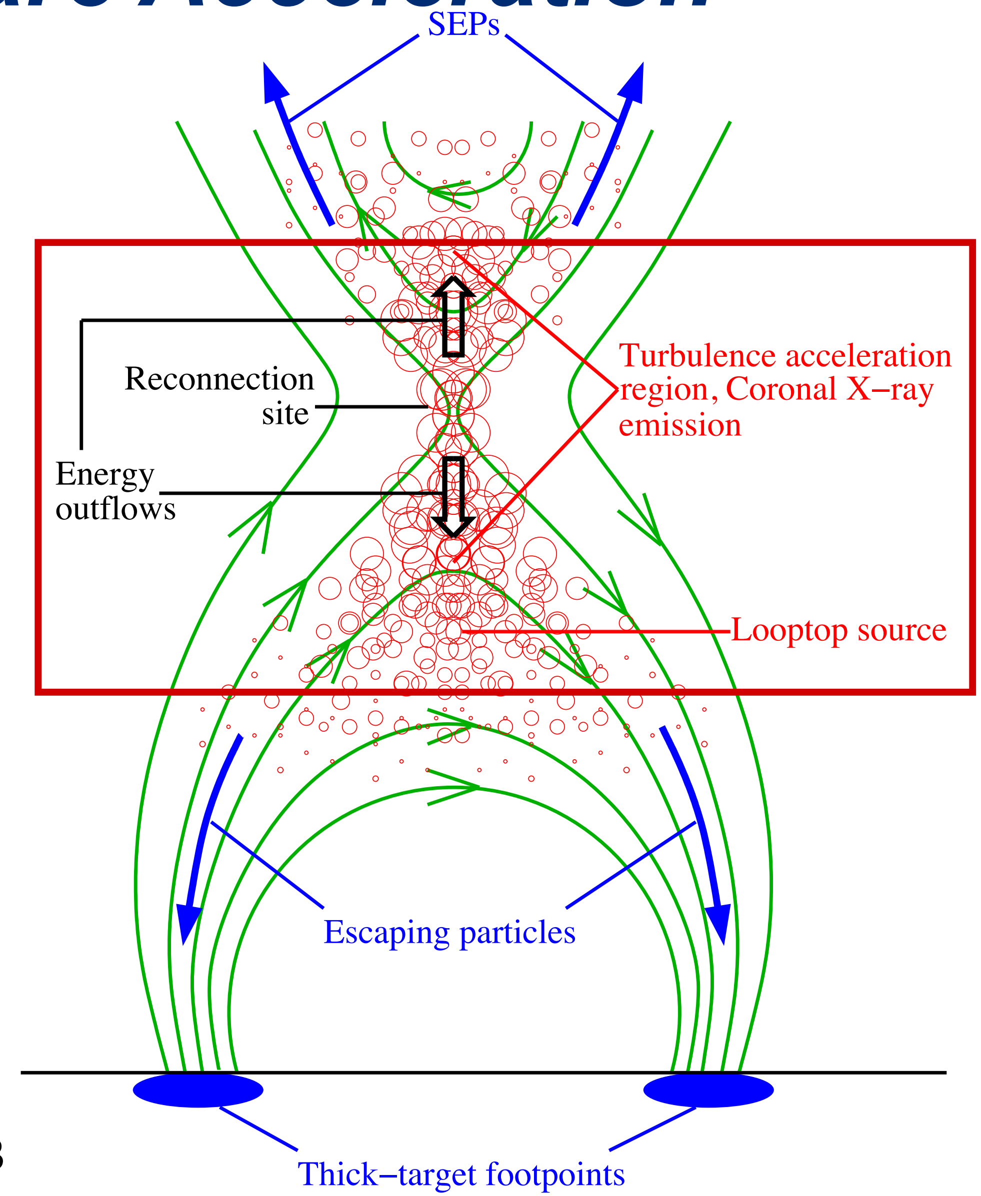
Cane et al, 1988

Evidence for Shock Acceleration

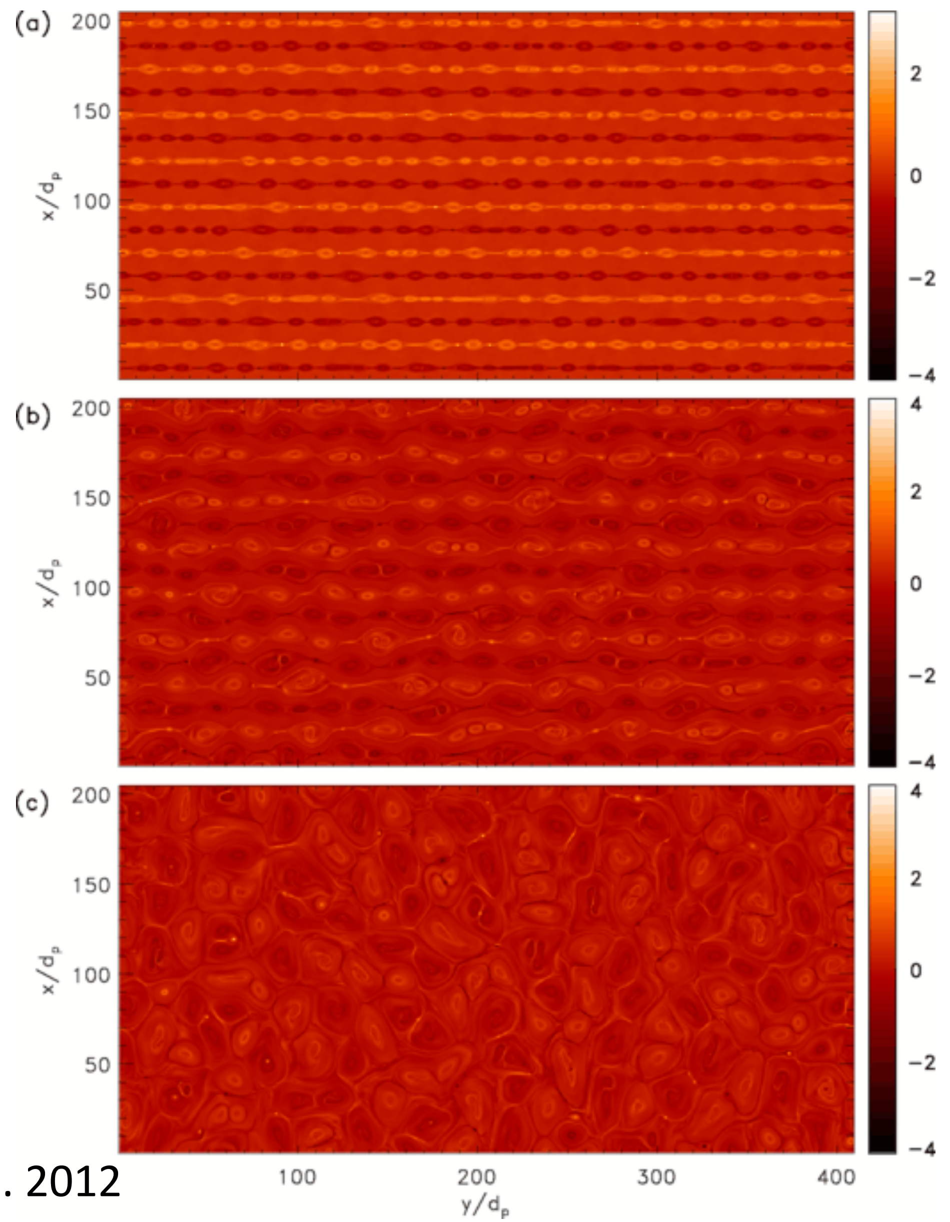


Mewaldt et al. 2005

2. Flare Acceleration

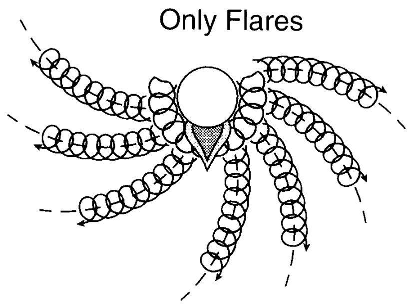


Liu et al. 2013



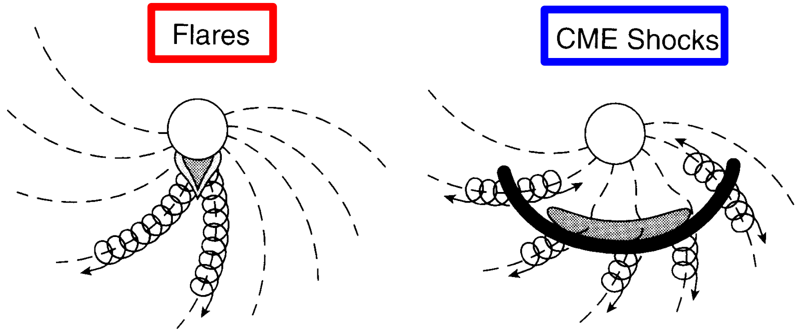
Drake et al. 2012

Old Picture:

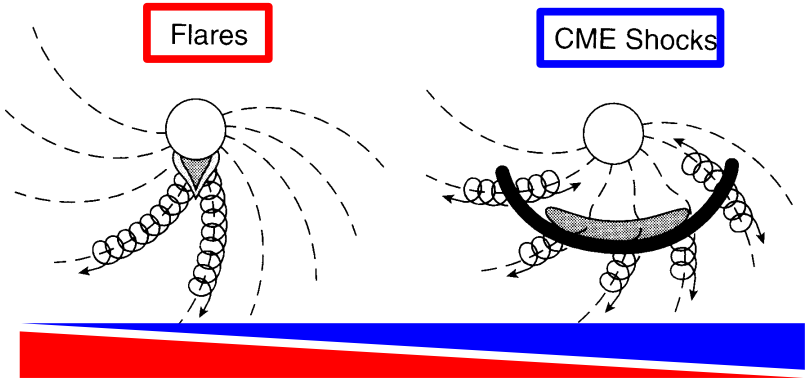


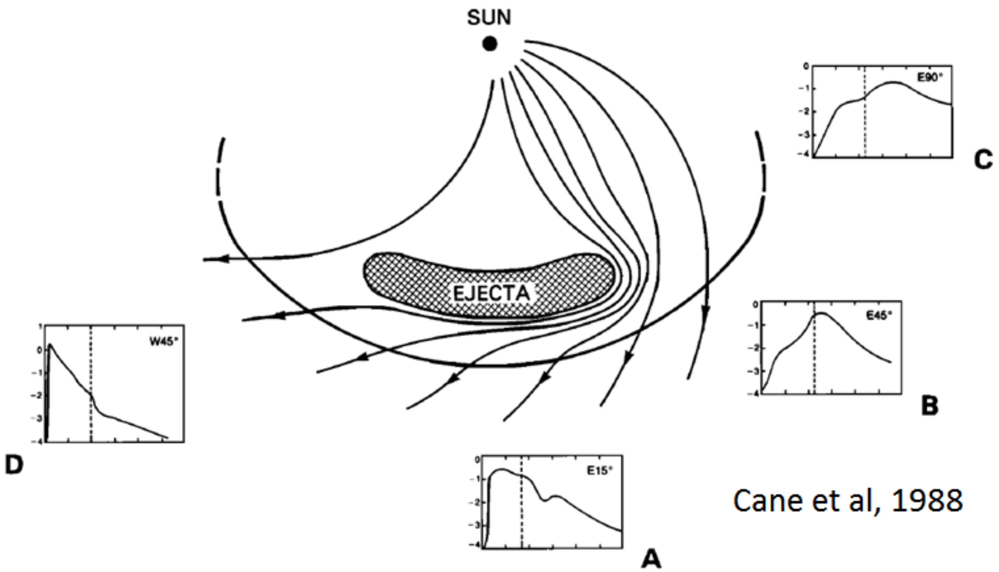
CME-driven shocks play an important role in accelerating particles
But….

~~New Picture:~~ Old new



New Picture:



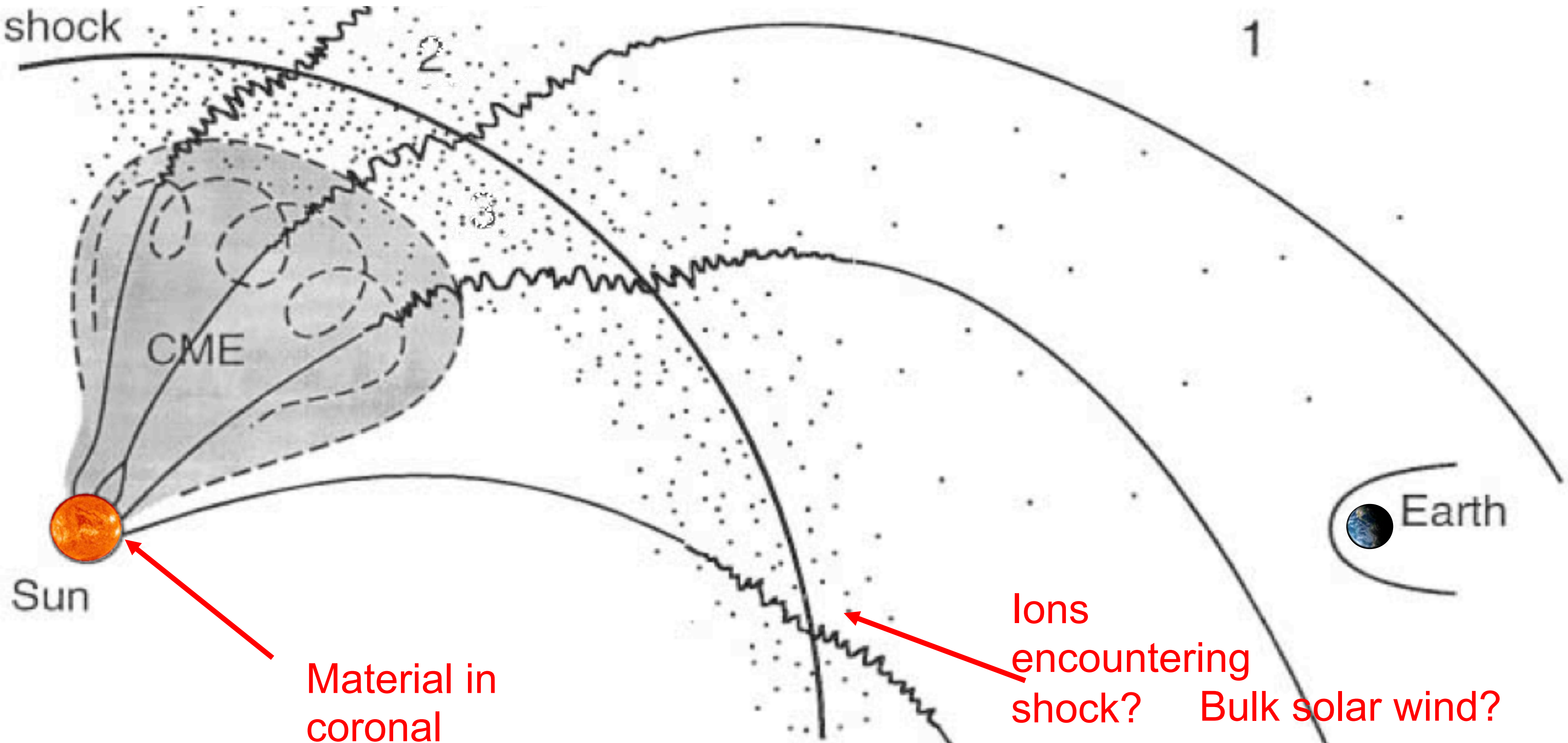


Cane et al, 1988

Life is more complicated:
Flares can contribute to shock-accelerated particles.
<u>Composition helps to understand how</u>

But it does not solve all problems!

What is being accelerated - seed population?



Material in coronal loops? (high T, Fe-rich?)

Ions encountering shock?

Bulk solar wind?

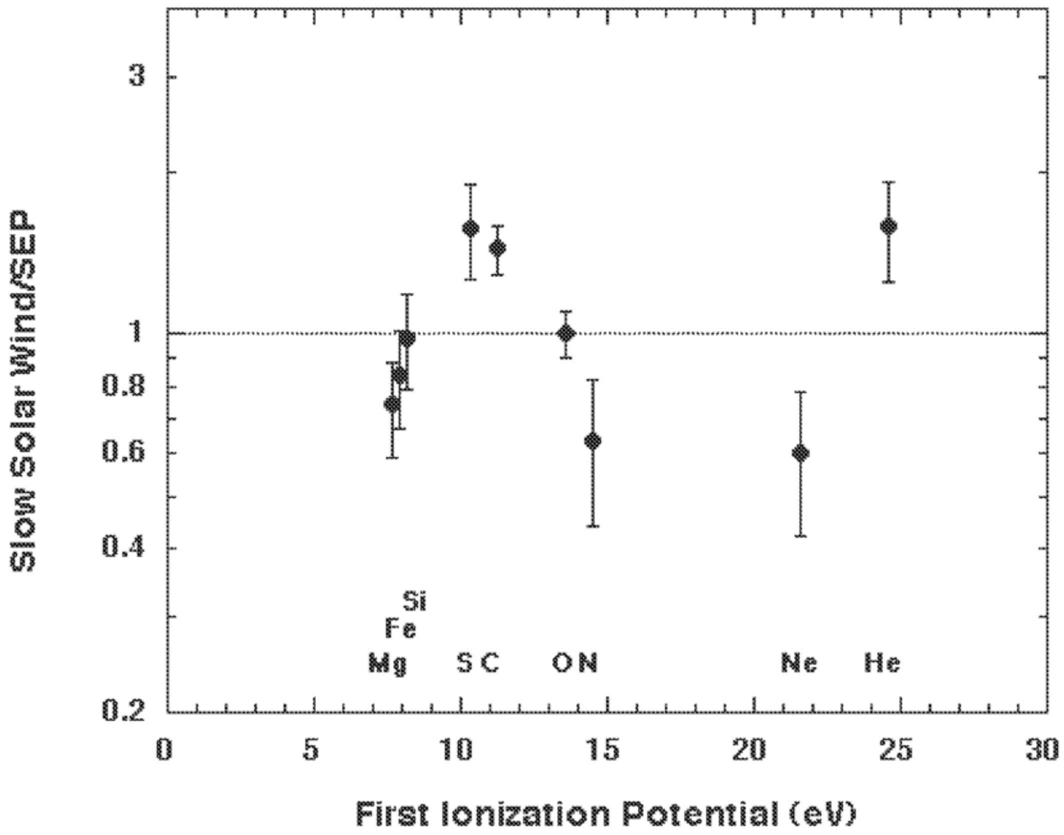
“Flare” particles?

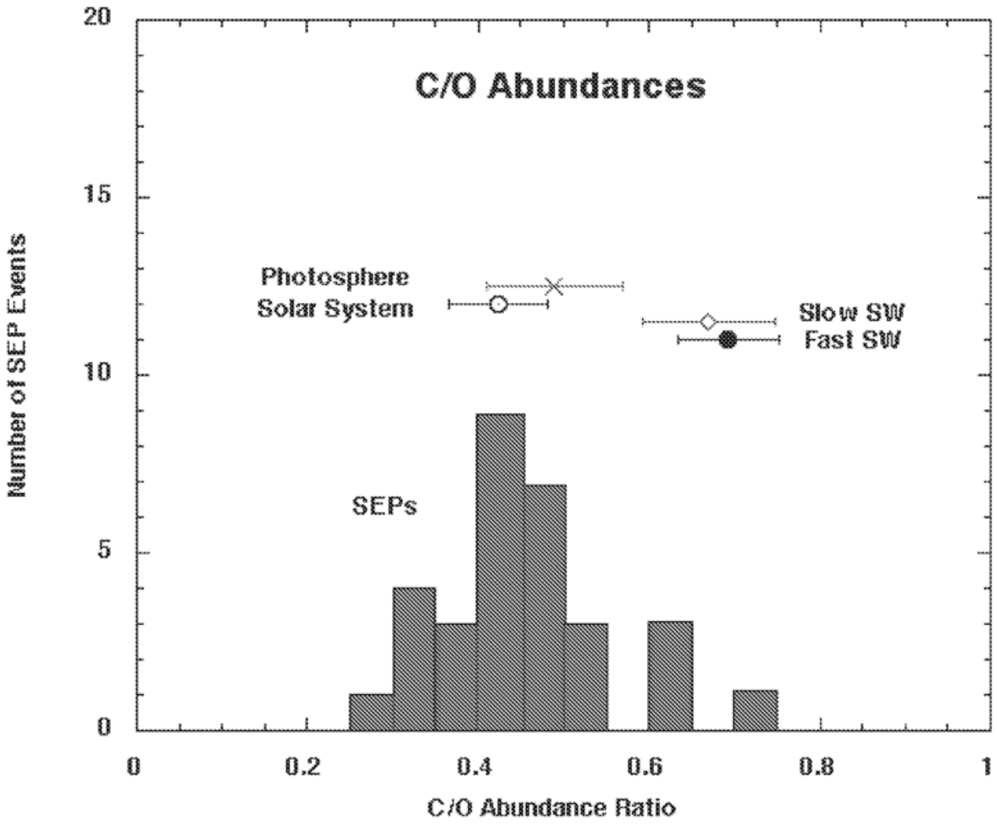
Suprathermal ions? -- what properties?

Adapted from Marty Lee, ApJS, 158, 2005

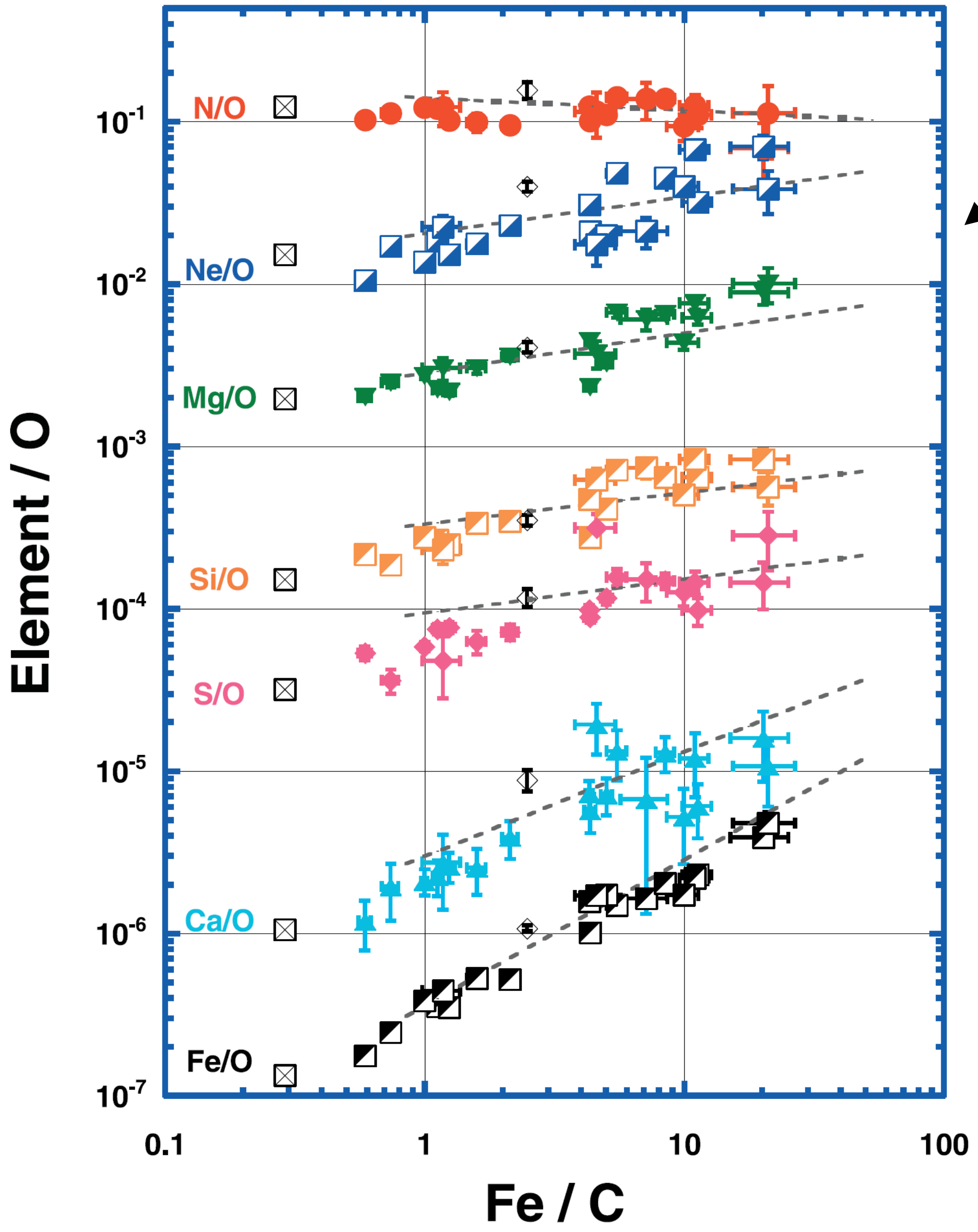
What is being accelerated?

- Solar Wind & SEP have different composition

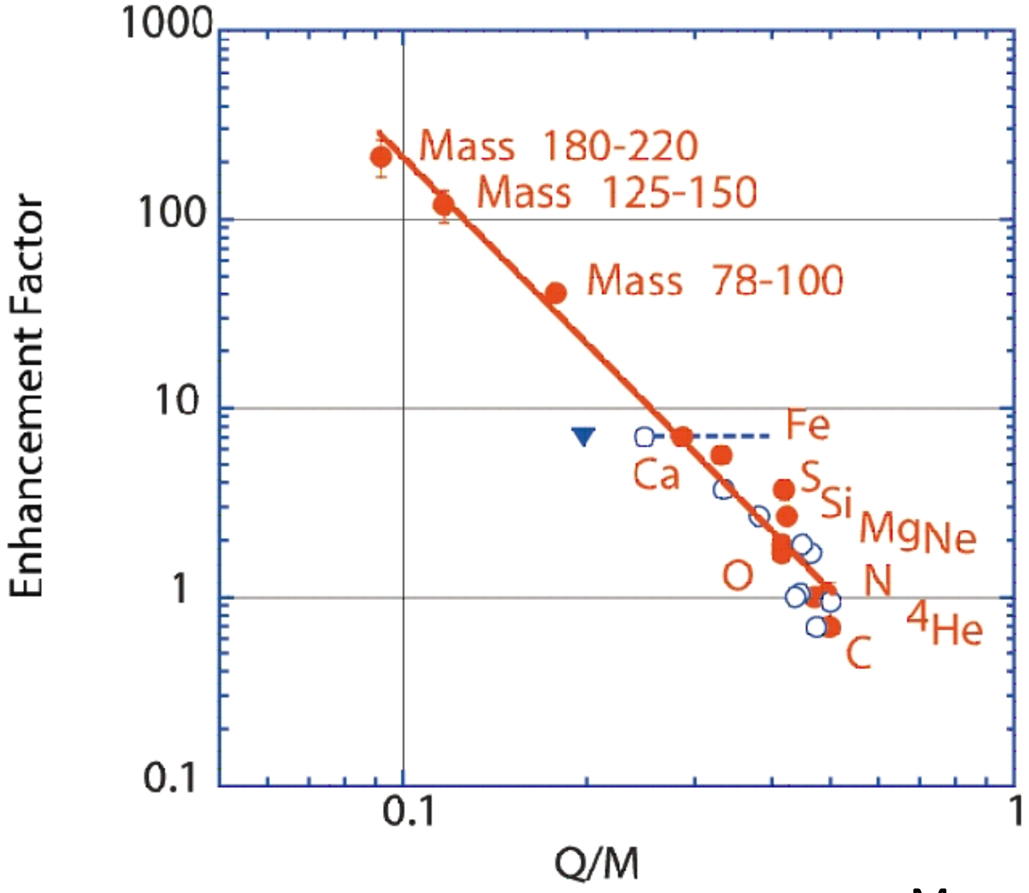




Mewaldt et al. 2001



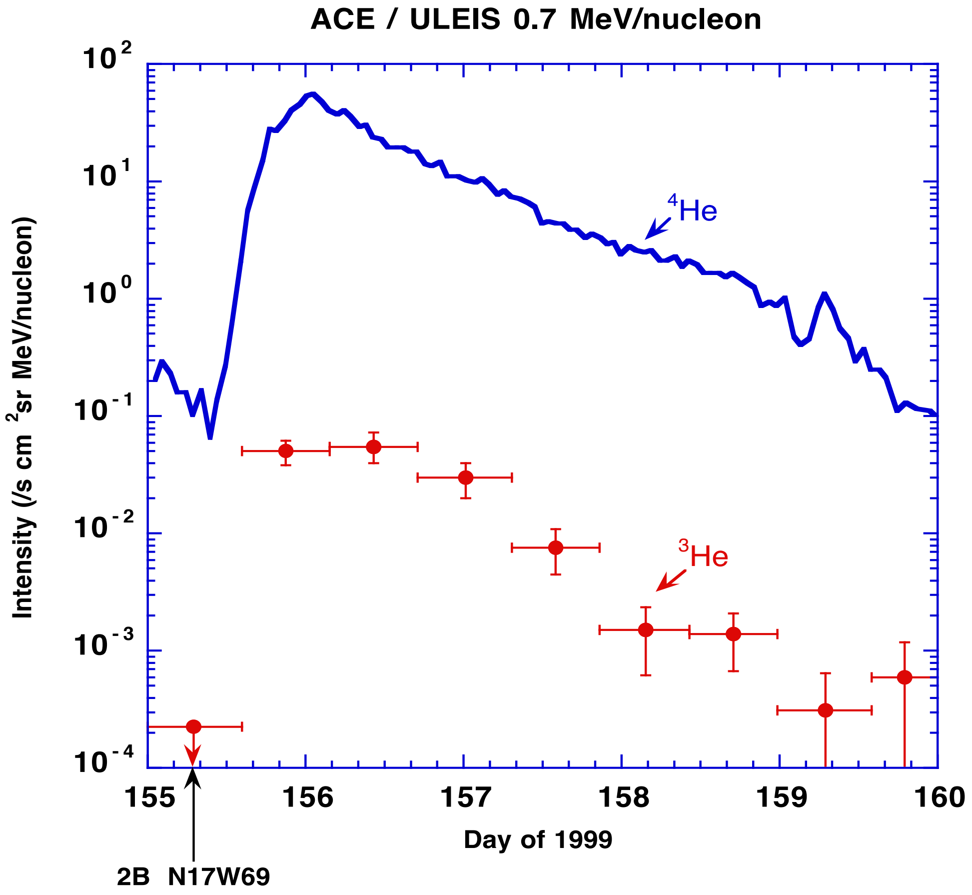
Heavy ion enhancements seen in solar energetic particles (Mason et al., 2004).
Could be due to wave-particle interactions.

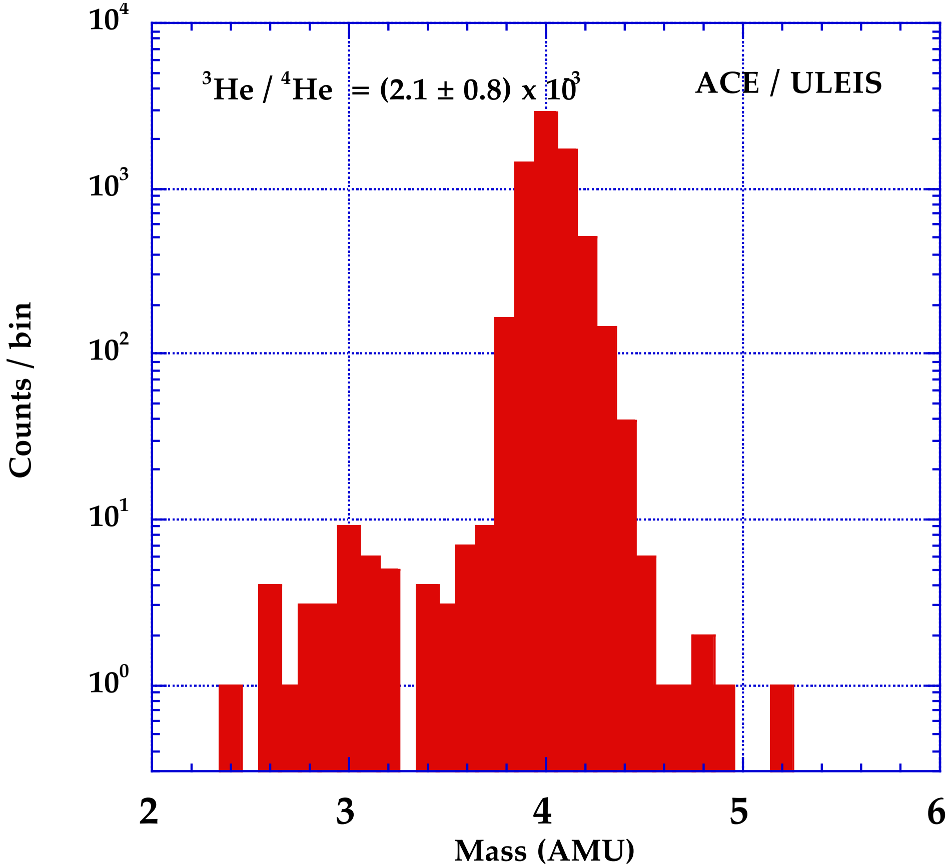


Mason et al., 2004

^{3}He in Gradual SEP Events

^{3}He abundance in ~50% of large SEP events >> solar wind value of ~5×10^{-4}





(Mason et al. 1999 ApJ, 525, L133).

^{3}He During Quiet-times

Time Variation of ^{3}He 119

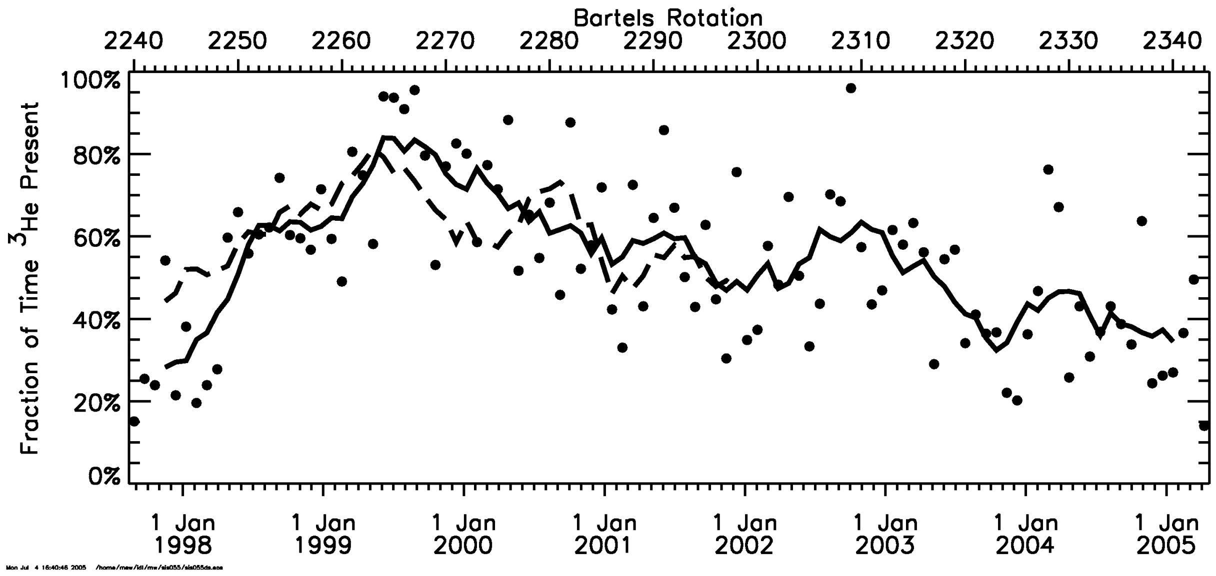


Figure 2. Time variation of the fraction of time when ^{3}He from impulsive SEP events is observed at 1 AU in any of the four energy intervals analyzed. The dashed curve is the smoothed result from our previous study [2] study. The solid curve is the smoothed result from the present study. The points indicate values obtained for individual Bartels rotations.

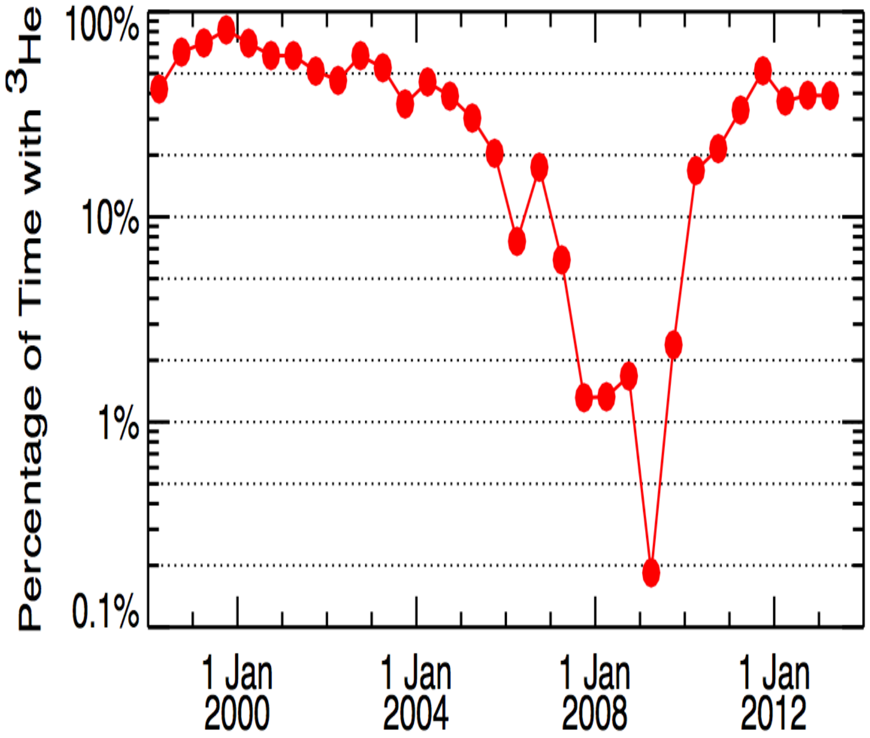
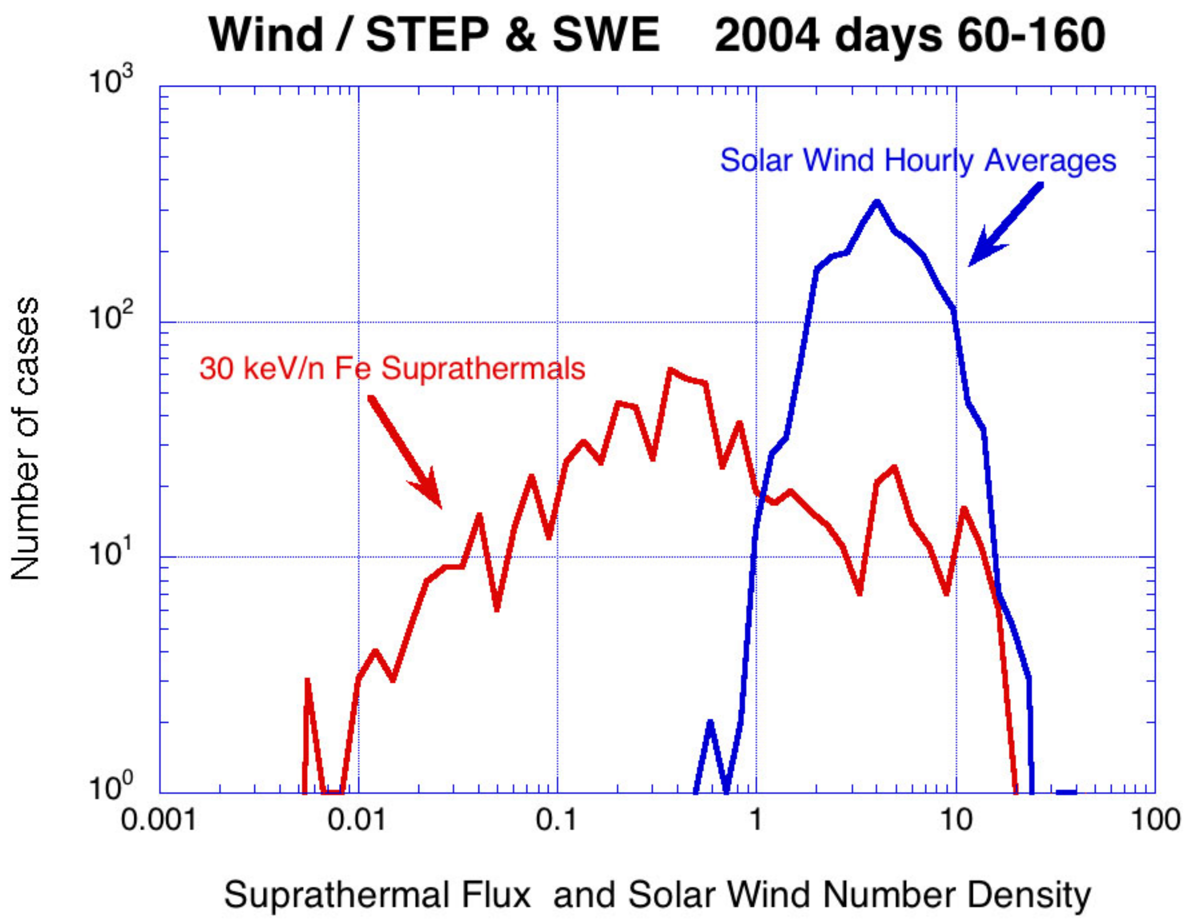


Figure 2. Average percentage of time that ^{3}He was detected at ACE during each 6-month period from the start of 1998 through mid-2013. All four of the energy intervals illustrated in Fig. 1 were used in identifying times when ^{3}He was present.

Widenbeck et al., ICRC, 2005

Wiedenbeck et al., AIP CP, 2014

The mystery of huge heavy ion (Fe) variations in intensity



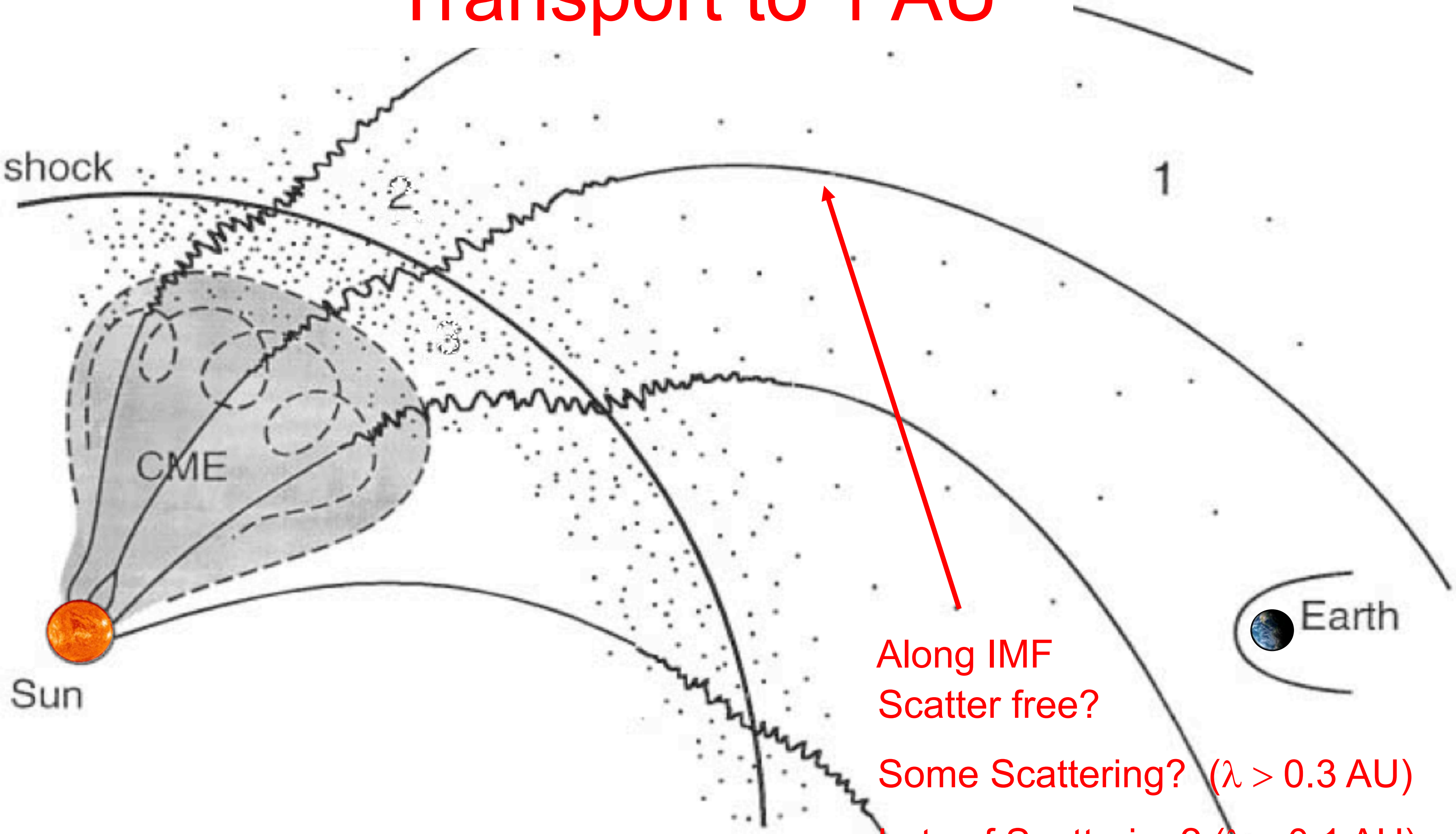
Mason et al., AIP CP781, 2005

Peak intensities in shock events vary over a range of ~10^4

- *not explained by CME speed*
- *not explained by shock acceleration models*
- *not explained by solar wind number density which does not change nearly as much*

Many researchers have suggested important role of suprathermal seed population

Transport to 1 AU



Along IMF

Scatter free?

Some Scattering? ($\lambda > 0.3$ AU)

Lots of Scattering? ($\lambda < 0.1$ AU)

Scattering λ dependent on time

And location?

Adapted from Marty Lee, ApJS, 158, 2005

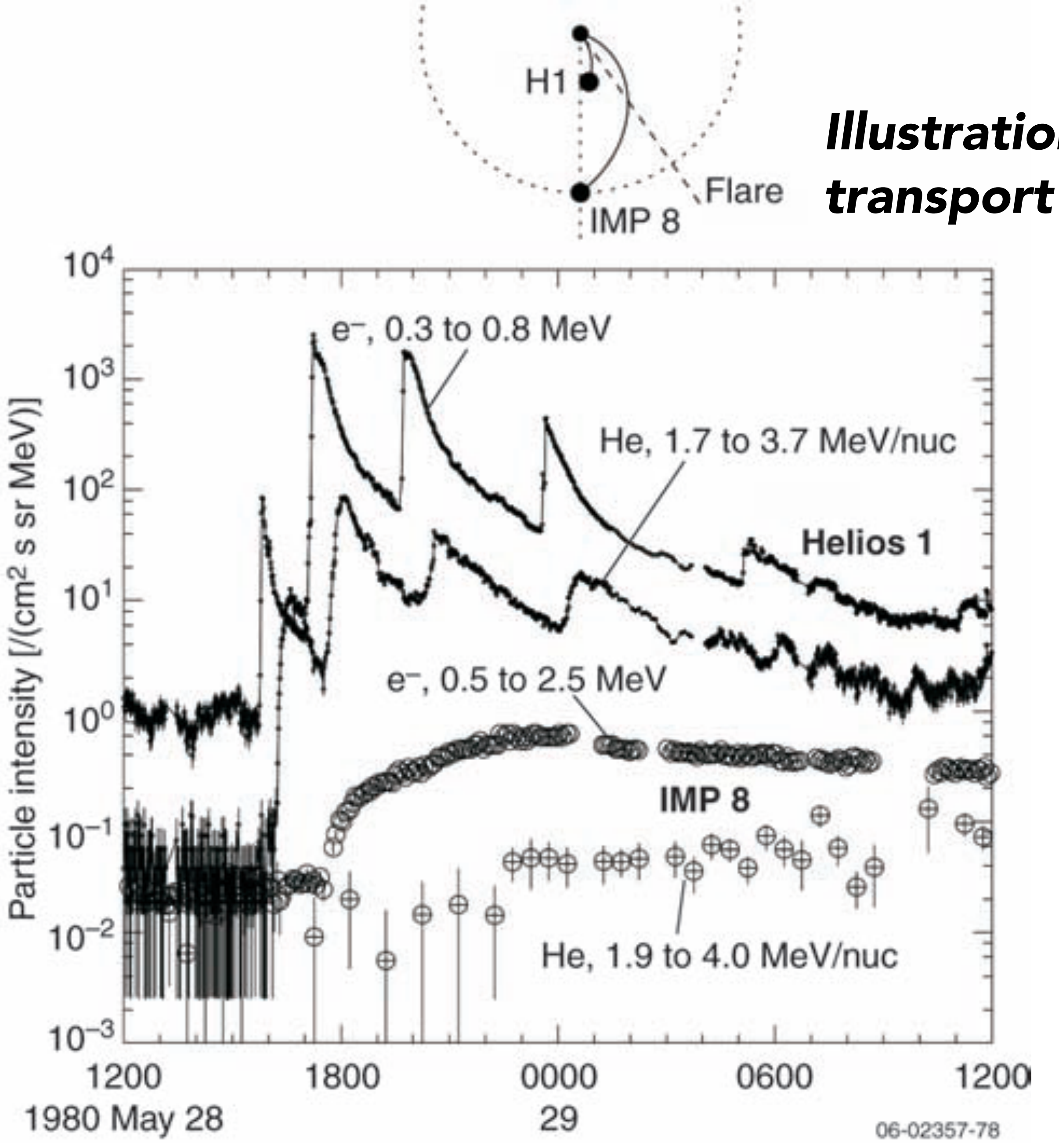


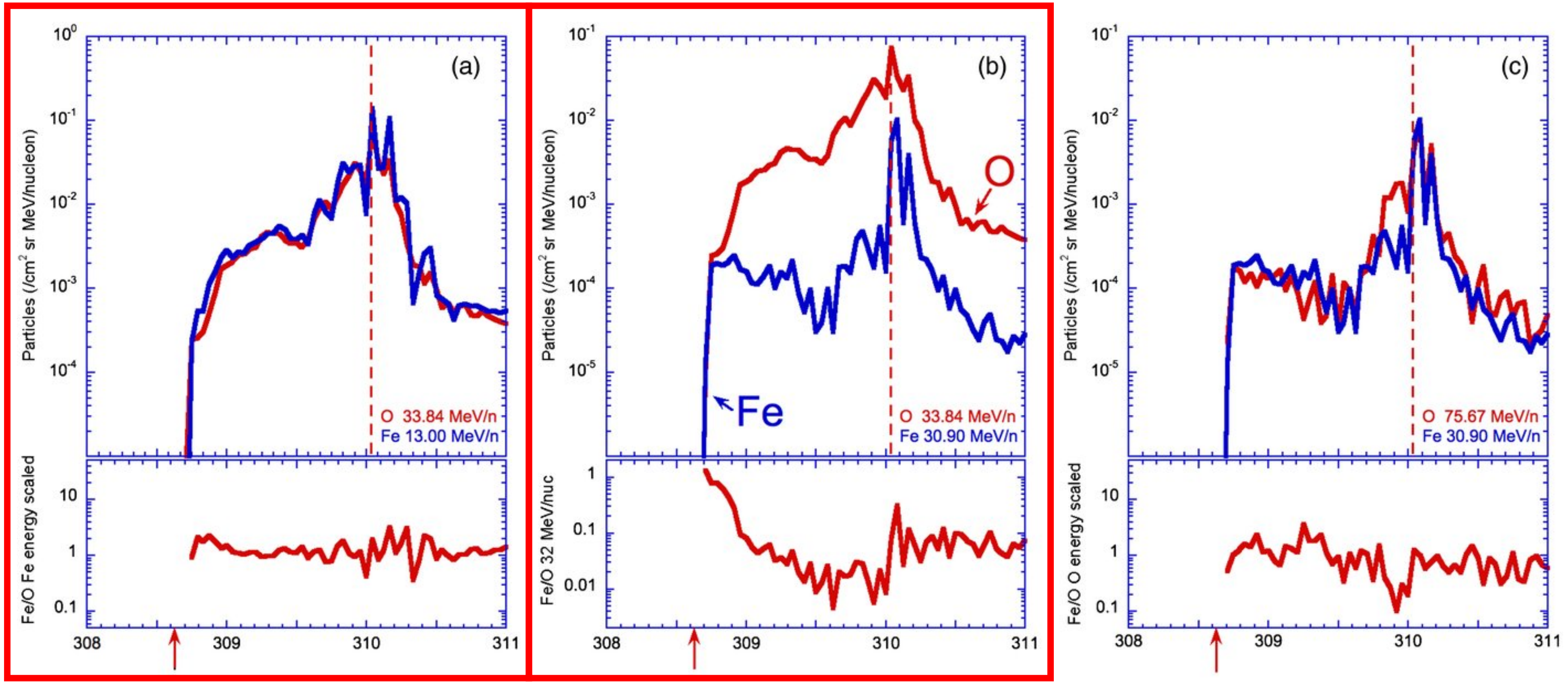
Illustration of the effect of transport on particles

Need Solar Orbiter, PSP to disentangle transport effects from injection effects.

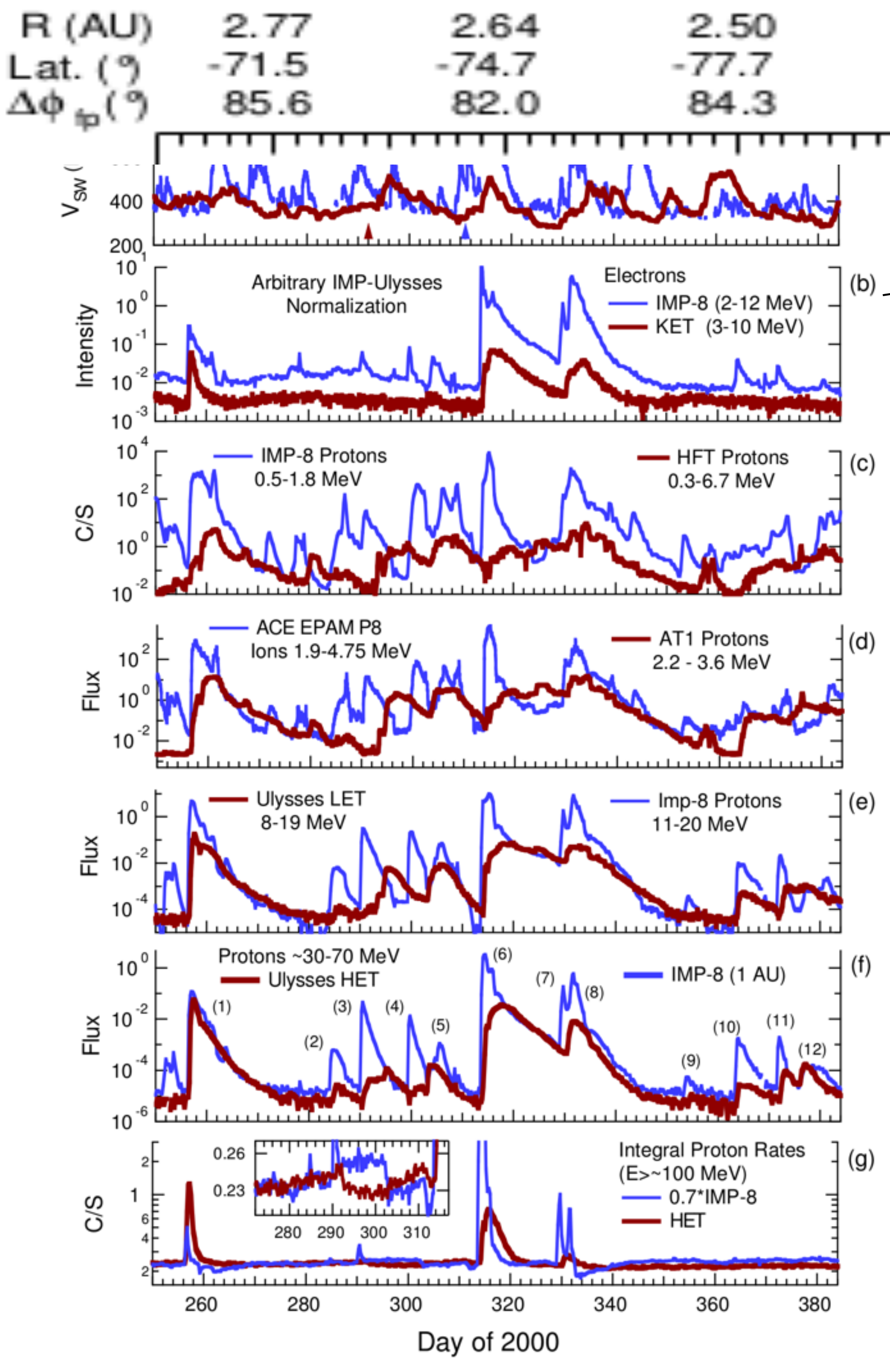
Wibberenz & Cane, 2006

Transport effects

- Common energy organizes better than velocity
  - Maybe rigidity is better



Mason et al. 2012



Blue: 1AU
Red: Ulysses (see above)
How does the Sun fill the heliosphere with energetic particles?

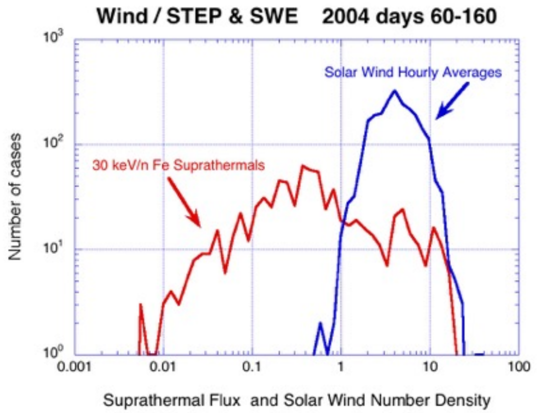
Note how the decay phases are all very similar.

This indicates that a large 'reservoir' of energetic particles that fills the heliosphere is being depleted at the same rate everywhere.

How is it filled?
Why does it empty in lockstep?
Measurements close to Sun!

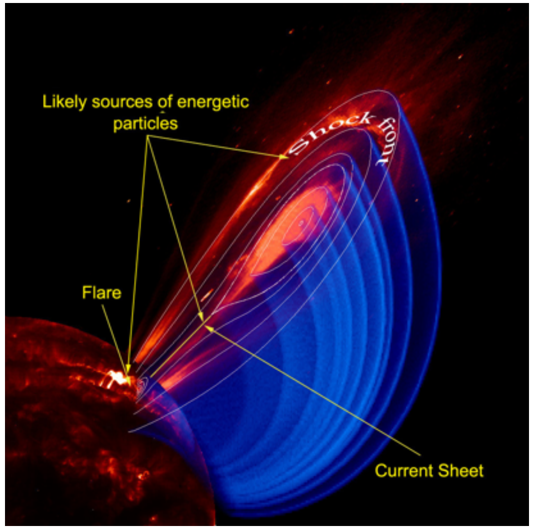
McKibben et al., 2003

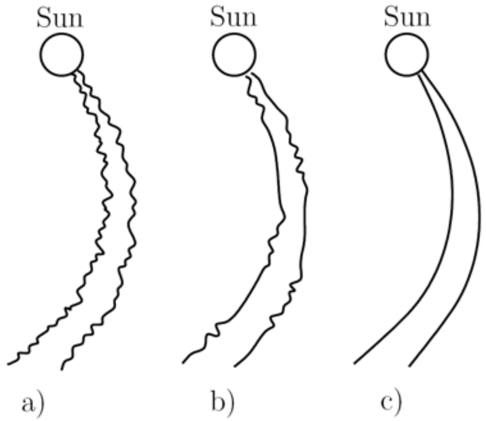
Outstanding Question



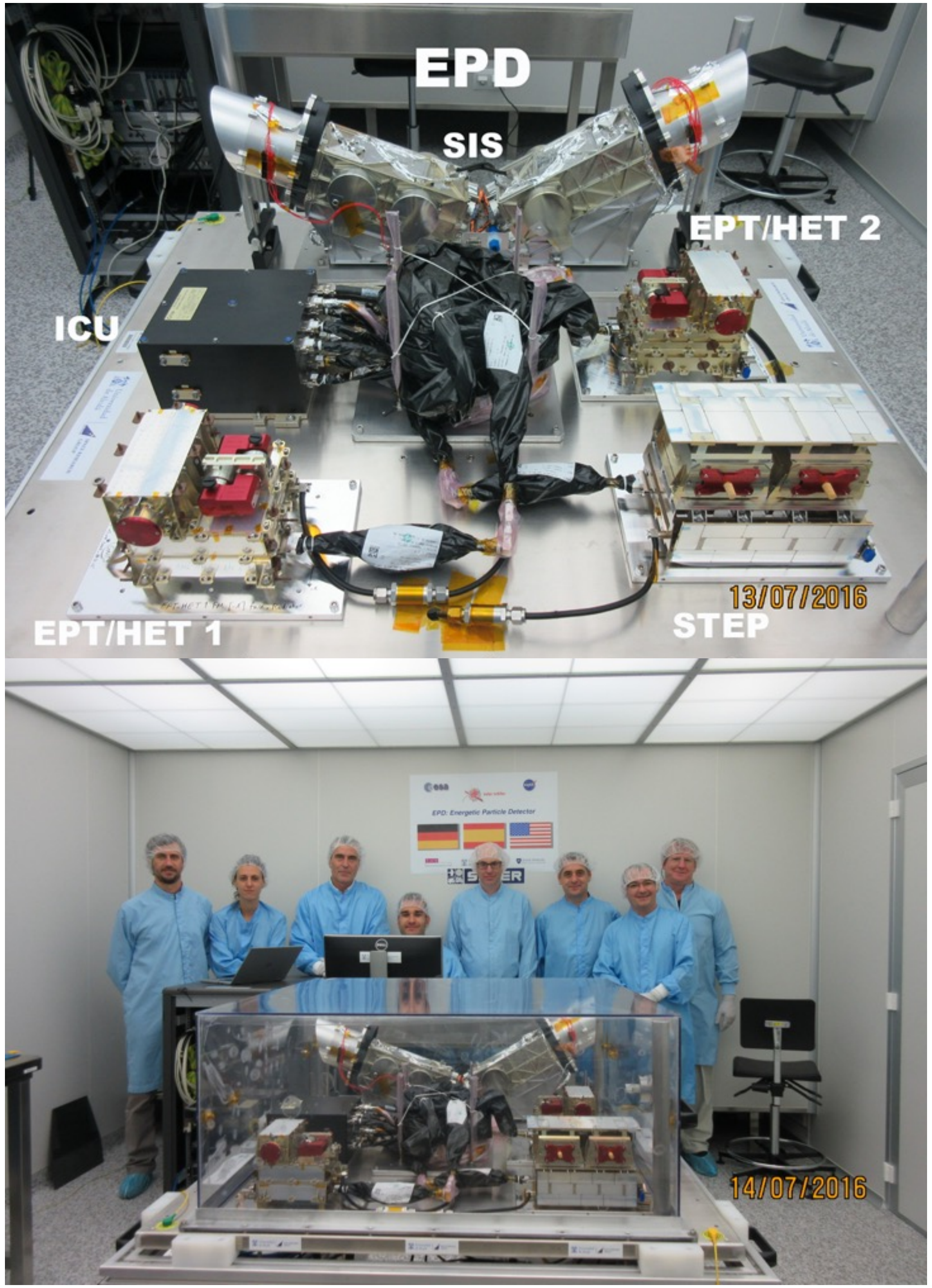
Injection (seed population important)

Acceleration (various processes)



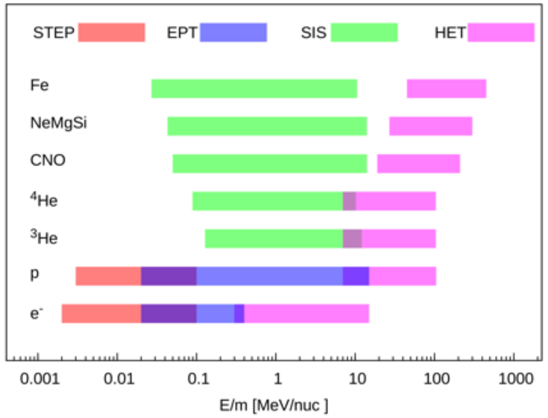


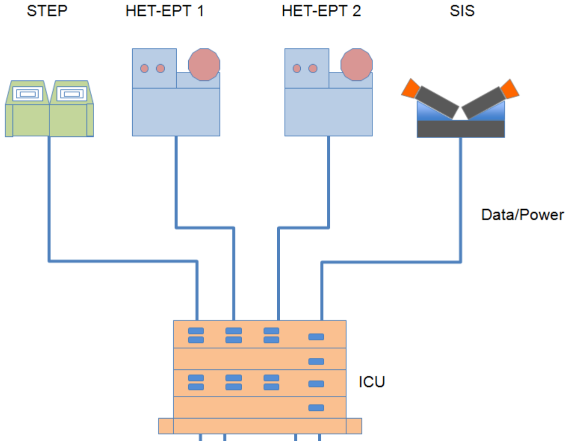
Transport (which smears out signatures)

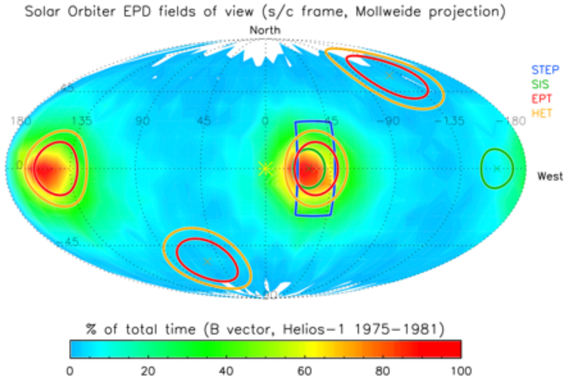


EPD is a suite of four sensors that measures suprathermal to high-energy particles:

- STEP (Suprathermal Electrons and Proton)
- EPT (Electron-Proton Telescope)
- SIS (Suprathermal Ion Spectrograph)
- HET (High-Energy Telescope)



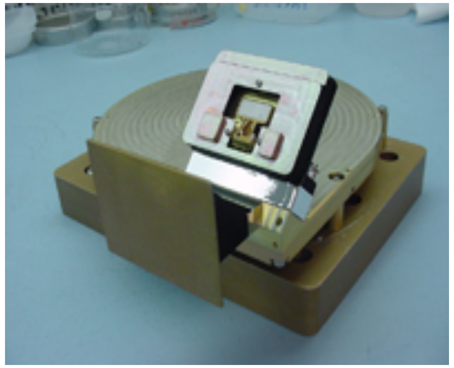


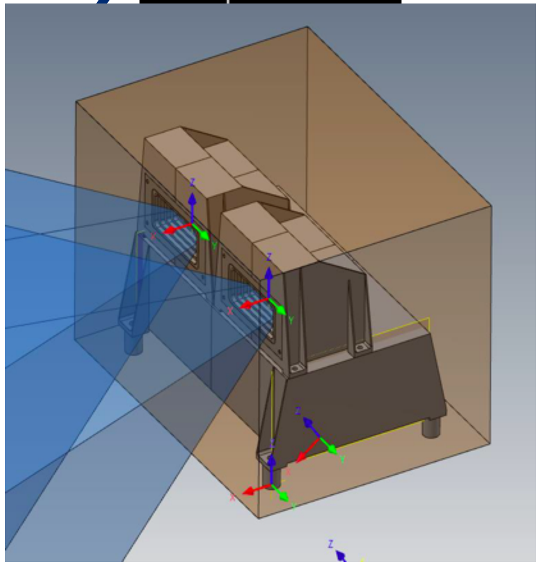


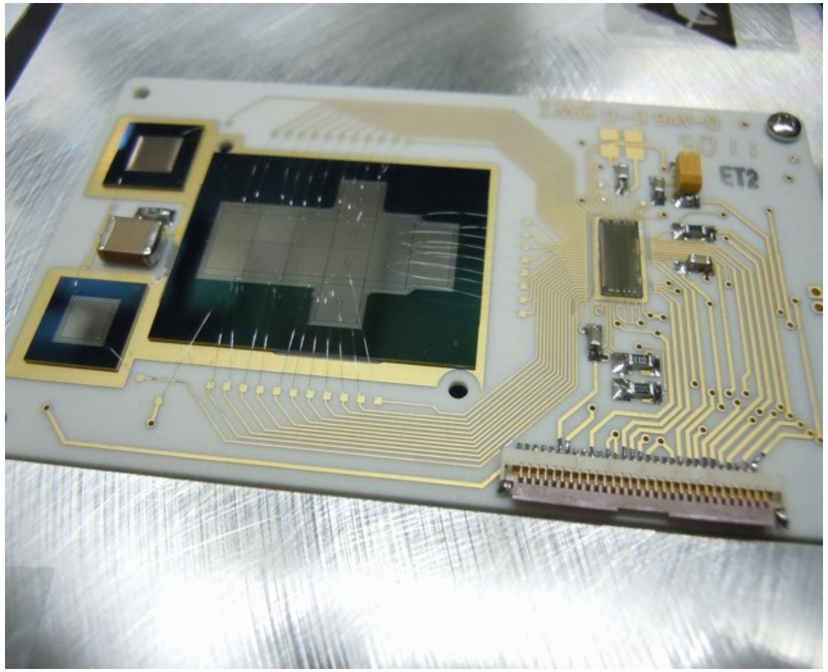
SupraThermal Electron and Proton (STEP)

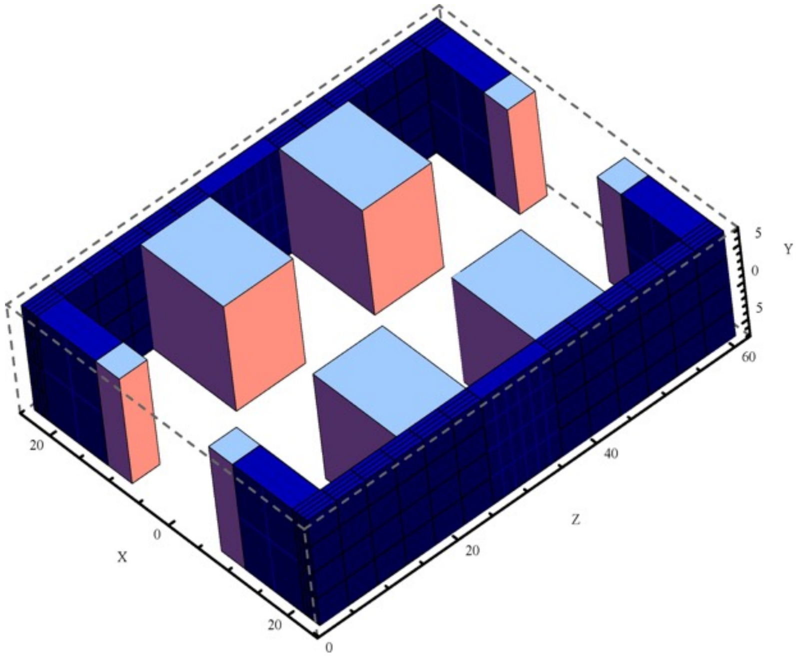
- S/C mounted
  - STEP will measure e^- [0.002-0.1MeV] and p^+ [0.003-0.1MeV]

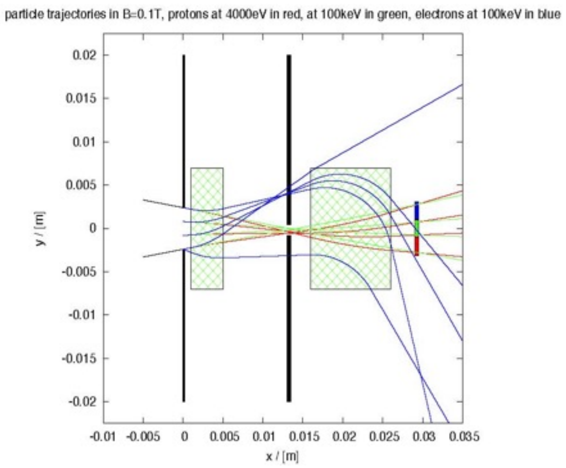
- Instrument Heritage:
  - STEP has heritage of STEREO/STE



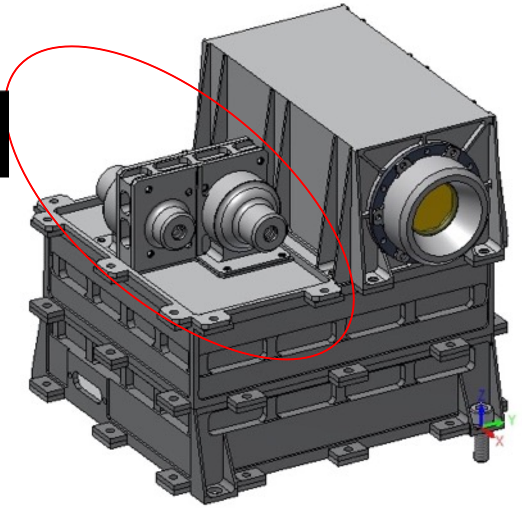




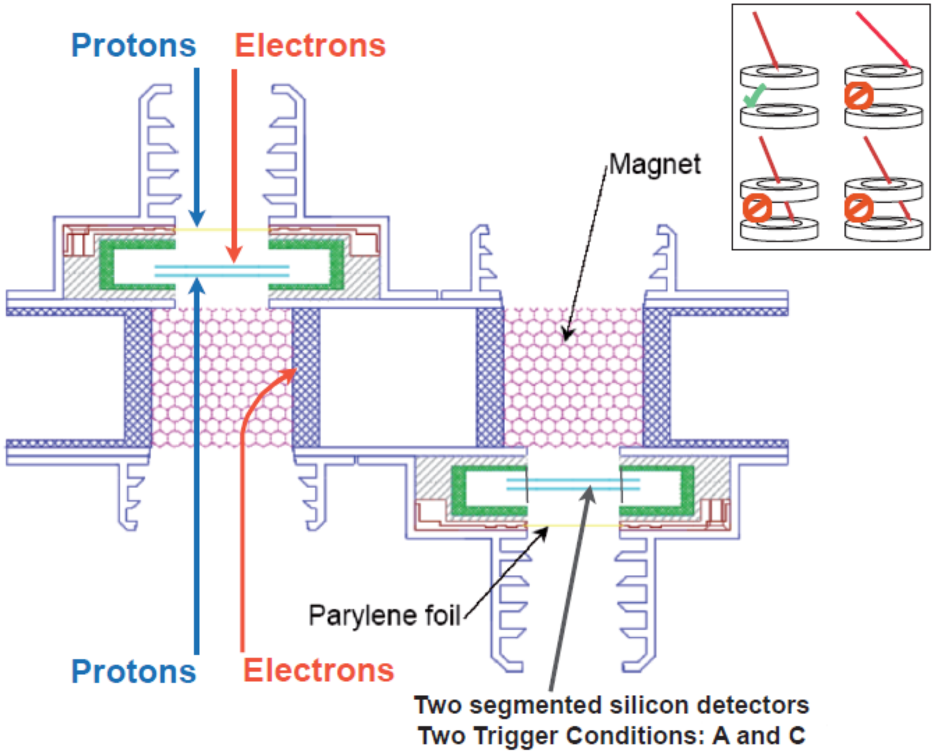


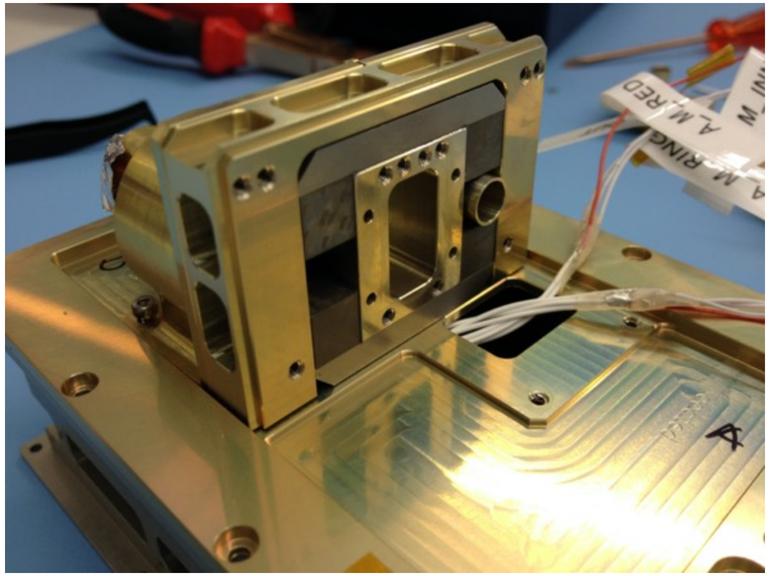


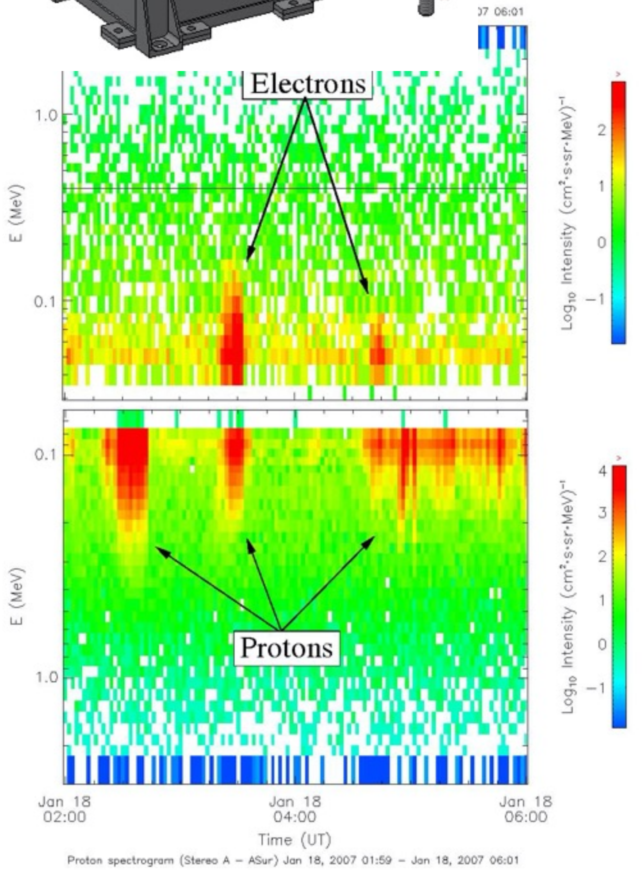
Electron Proton Telescope (EPT)



- Measures electrons and protons
  - EPT will measure e^- [0.02-0.7 MeV], p^+ [0.02-7 MeV]
  - Four view directions (in and out of orbital plane) with two units
  - EPT and HET sensors share the same Electronic Box
- Instrument Heritage:
  - EPT has direct heritage from STEREO/SEPT

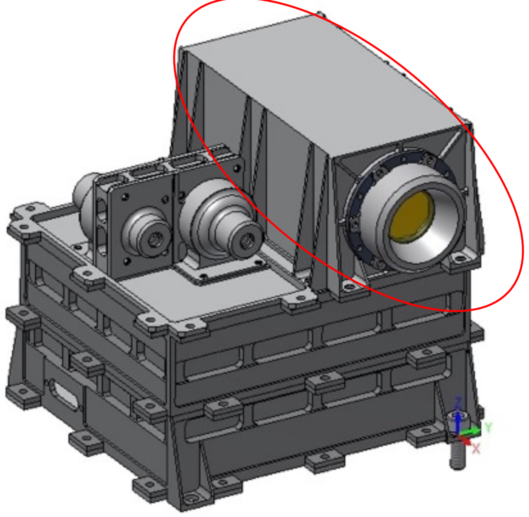


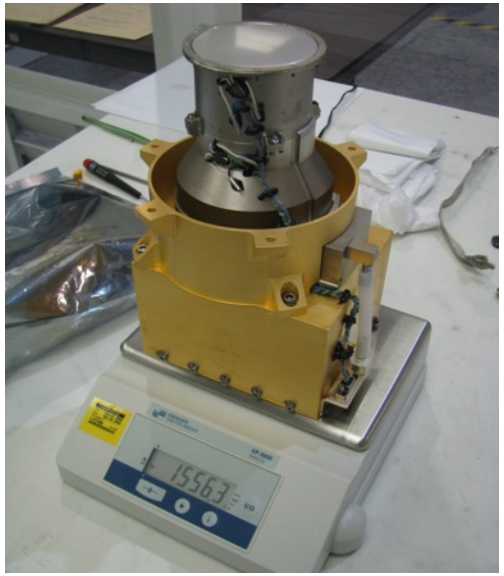


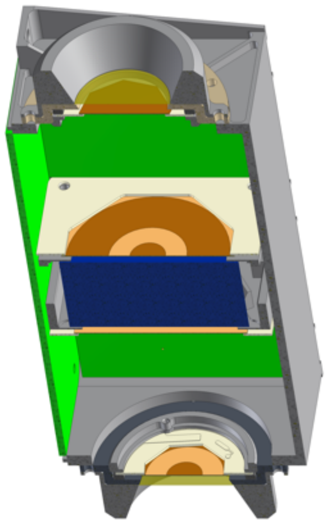


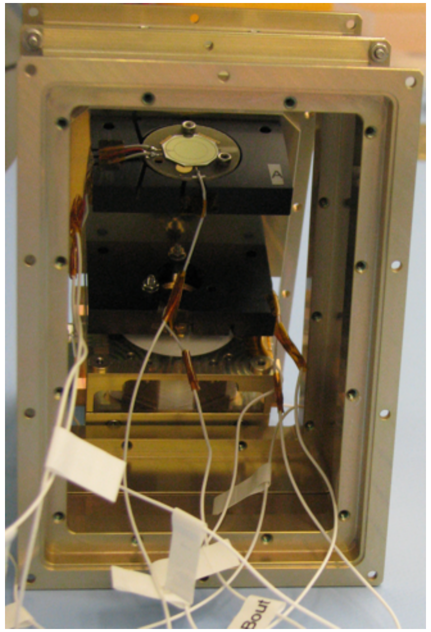
High-Energy Telecope (HET)

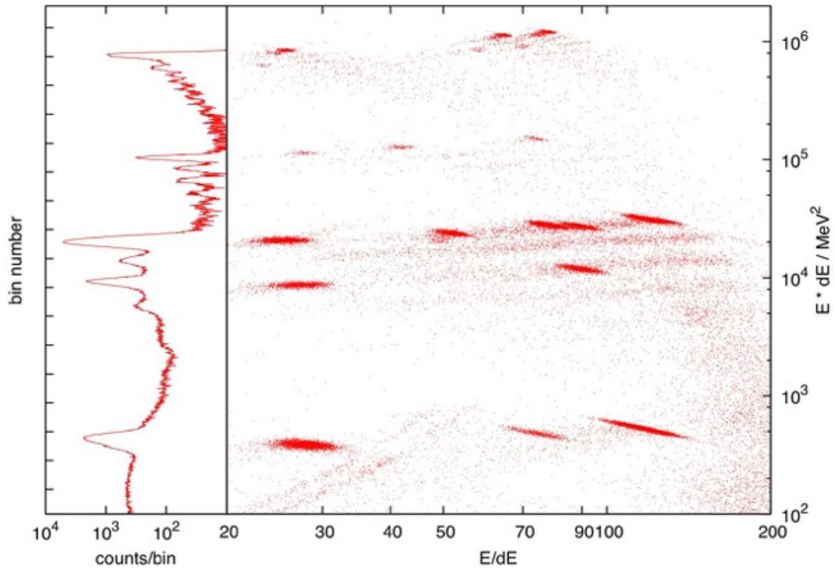
- Measures e- [0.3-20MeV], p+ [10-100MeV] and ions [50-200MeV/nuc **Z-dependent]
  - Two view directions (in and out of orbital plane) with two units
  - EPT and HET sensors share the same Electronics Box
- Instrument Heritage:
  - HET has heritage from the MSL/RAD instrument







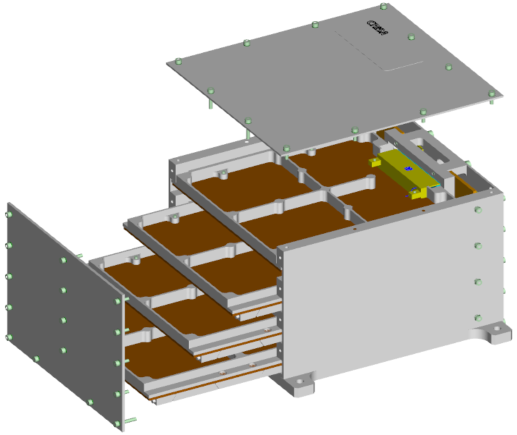




Integrated Control Unit (ICU)

Universidad de Alcalá

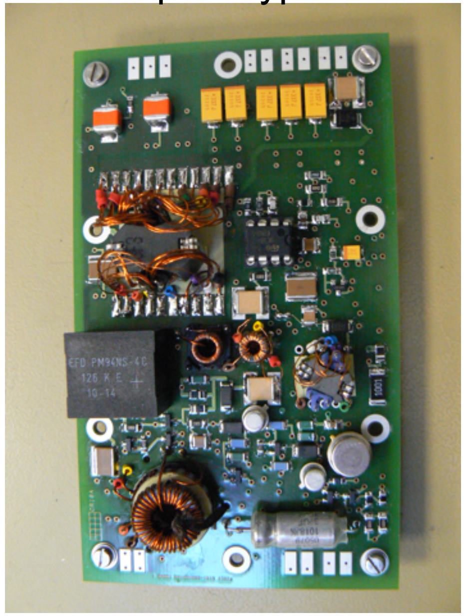
- Provides a single point of connection between the S/C and all the EPD sensors
  - Power I/F
  - Data I/F
  - Cold redundant configuration
- Heritage
  - ICU has heritage from SOHO/COSTEP CDPU



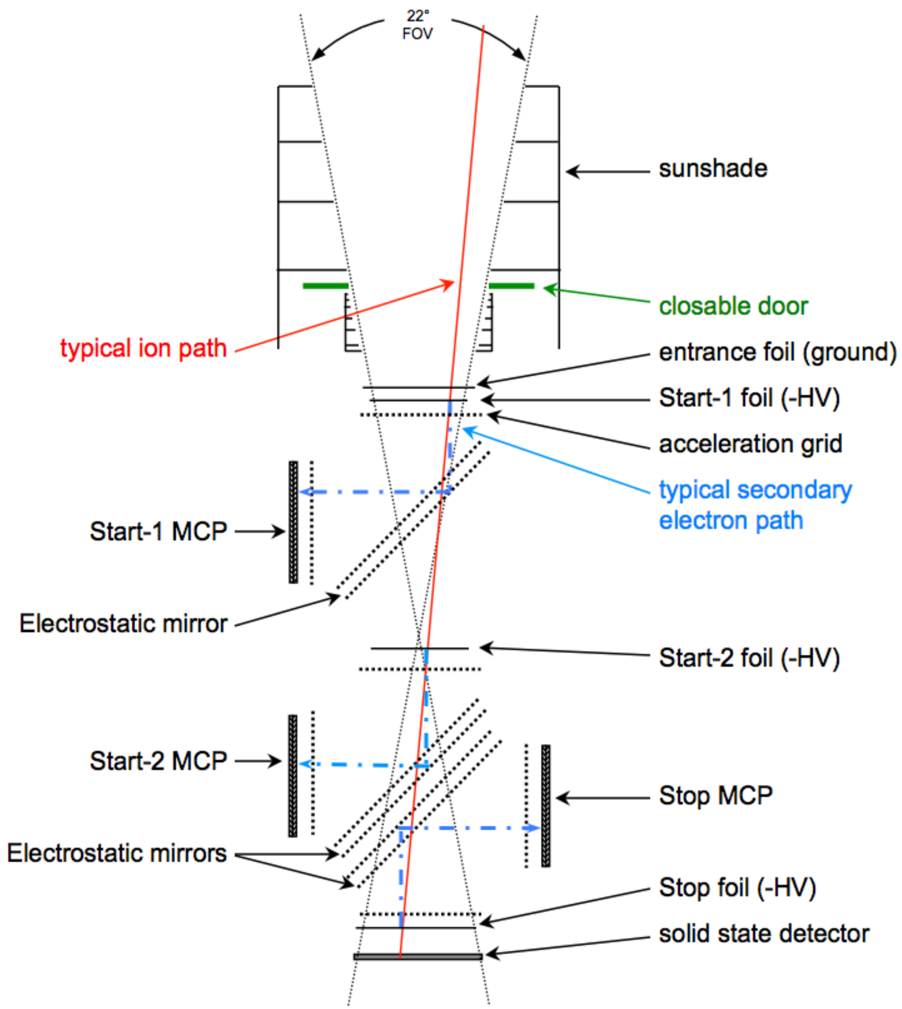
ICU emulator

ICU prototype

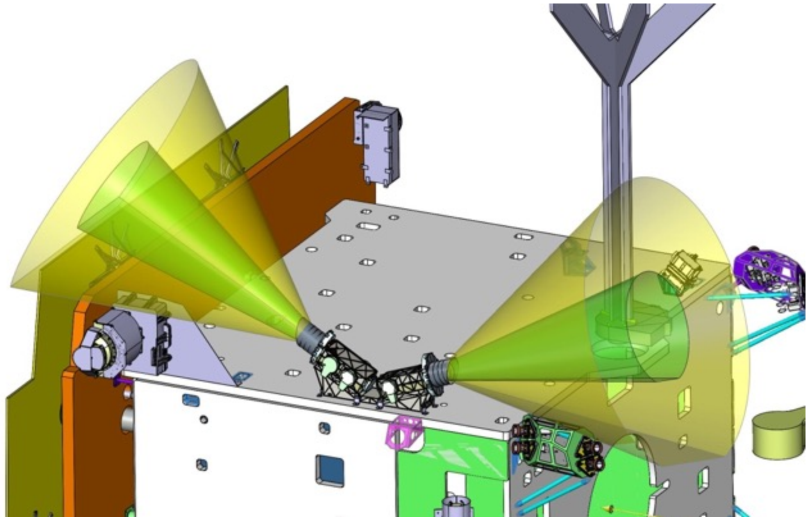
LVPS prototype

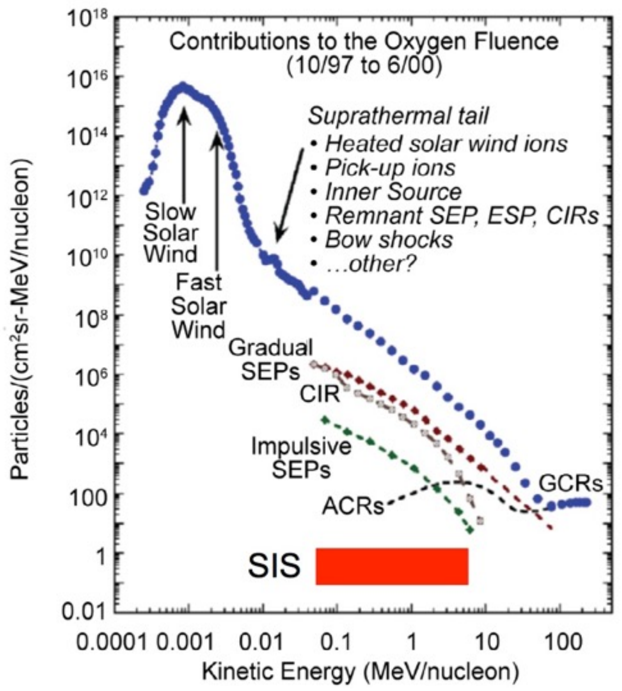


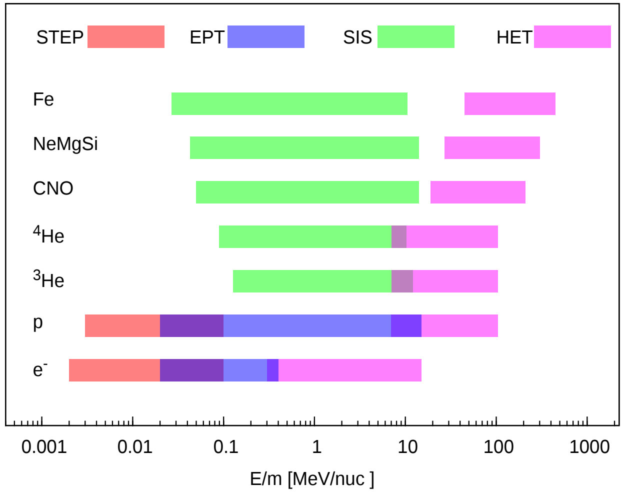
Suprathermal Ion Spectrograph (SIS)



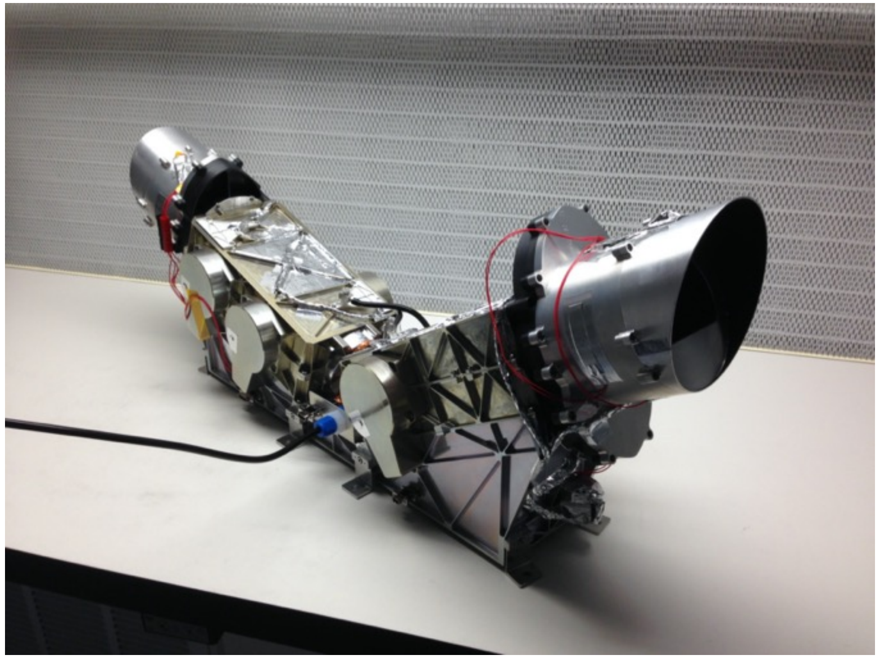
- **SIS is a Time-of-Flight by Energy high-resolution ion mass spectrometer**
- **Two identical telescopes measure the ion mass and energy**
- **Same measurement technique as was used on ACE/ULEIS**

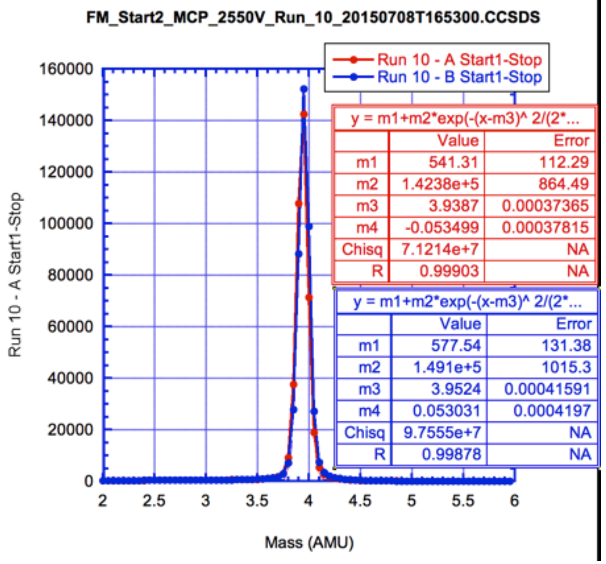






SIS-Flight Model



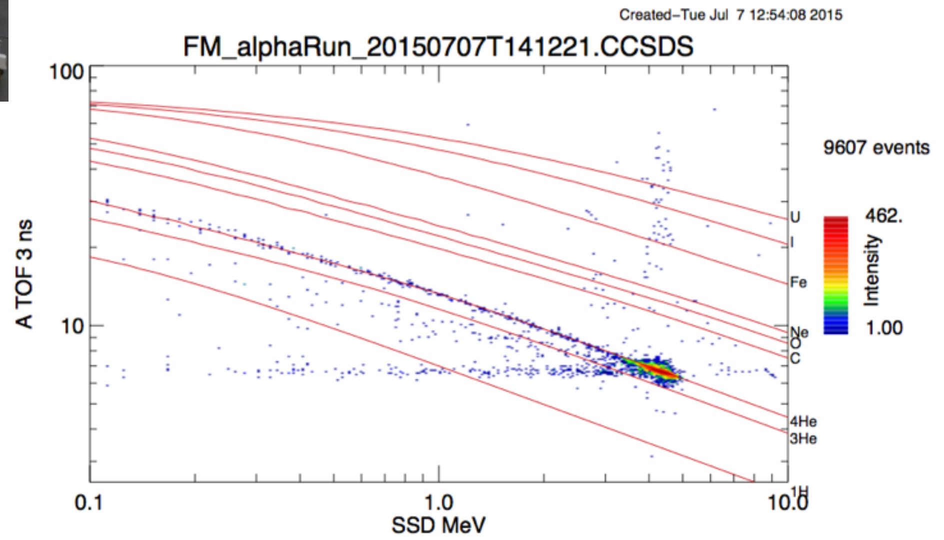


He histograms with TOF-1

m/sigma-m:

A telescope: 73.6

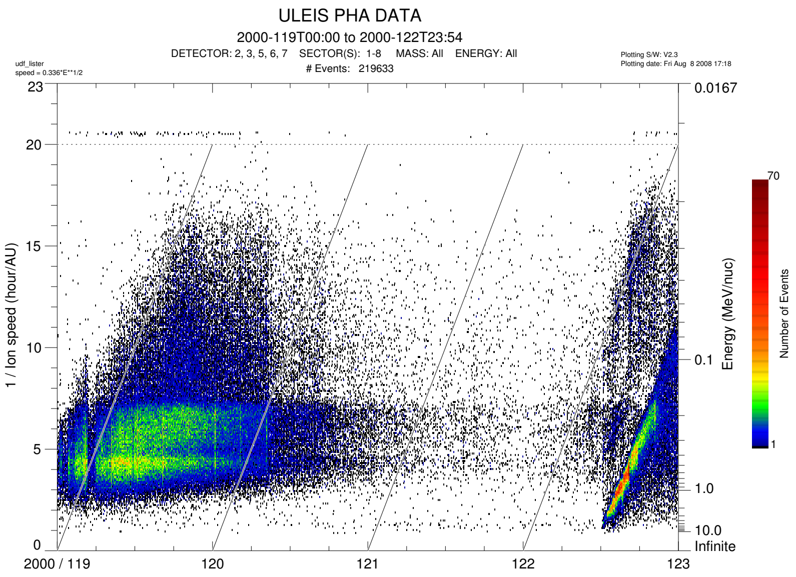
B telescope: 74.5

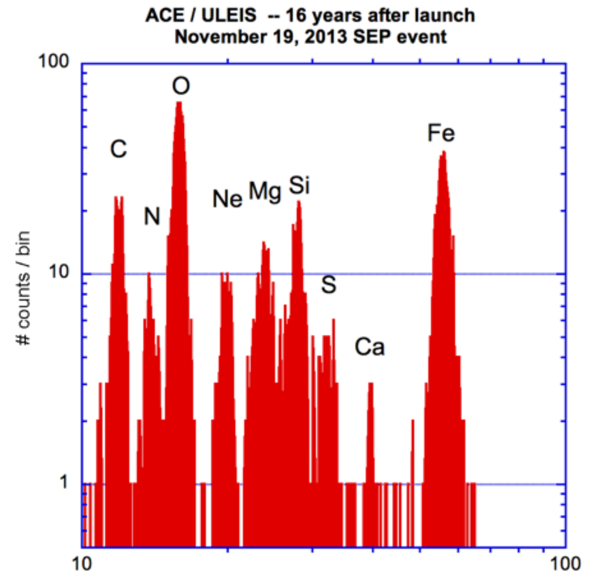


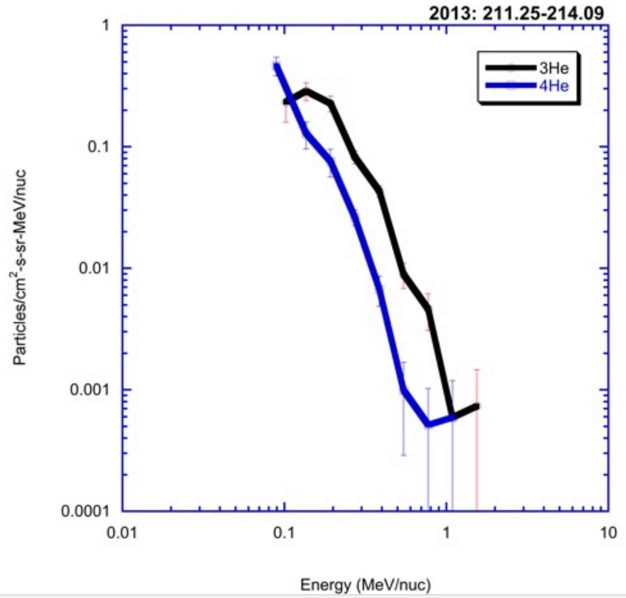
- SIS Flight Model
- FM met and exceeded all the L1 requirements:
    - Energy resolution (<5%)
    - Energy range (0.05 – 10 MeV/nuc)
    - Mass resolution (*m/dm* > 50)
    - Etc.

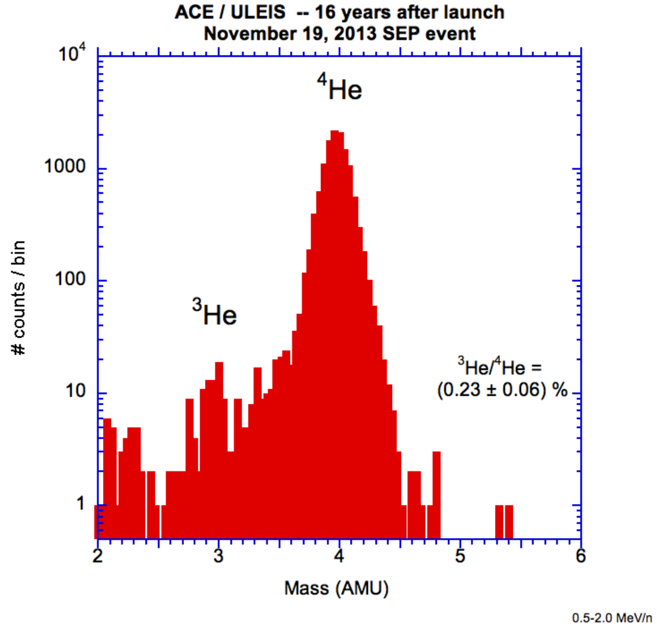
SIS Data Products

- **Energy Range**
  - 50 keV/nuc – 10 MeV/nuc
- **Three science data products**
  - Matrix rates for 12 major elements
  - (H, 3He, 4He, C, N, etc)
  - Pulsed Height Analyzer Events
  - Helium Histogram *New*
- **Time Cadences**
  - Nominal 30 s
  - Burst 3 s
  - Quick look 30 minutes
- **Two look directions *New***
  - Sunward 30º off the deck; Anti-sunward 20º off the deck
  - Each has an iris mechanism to control aperture from 100% to 1%

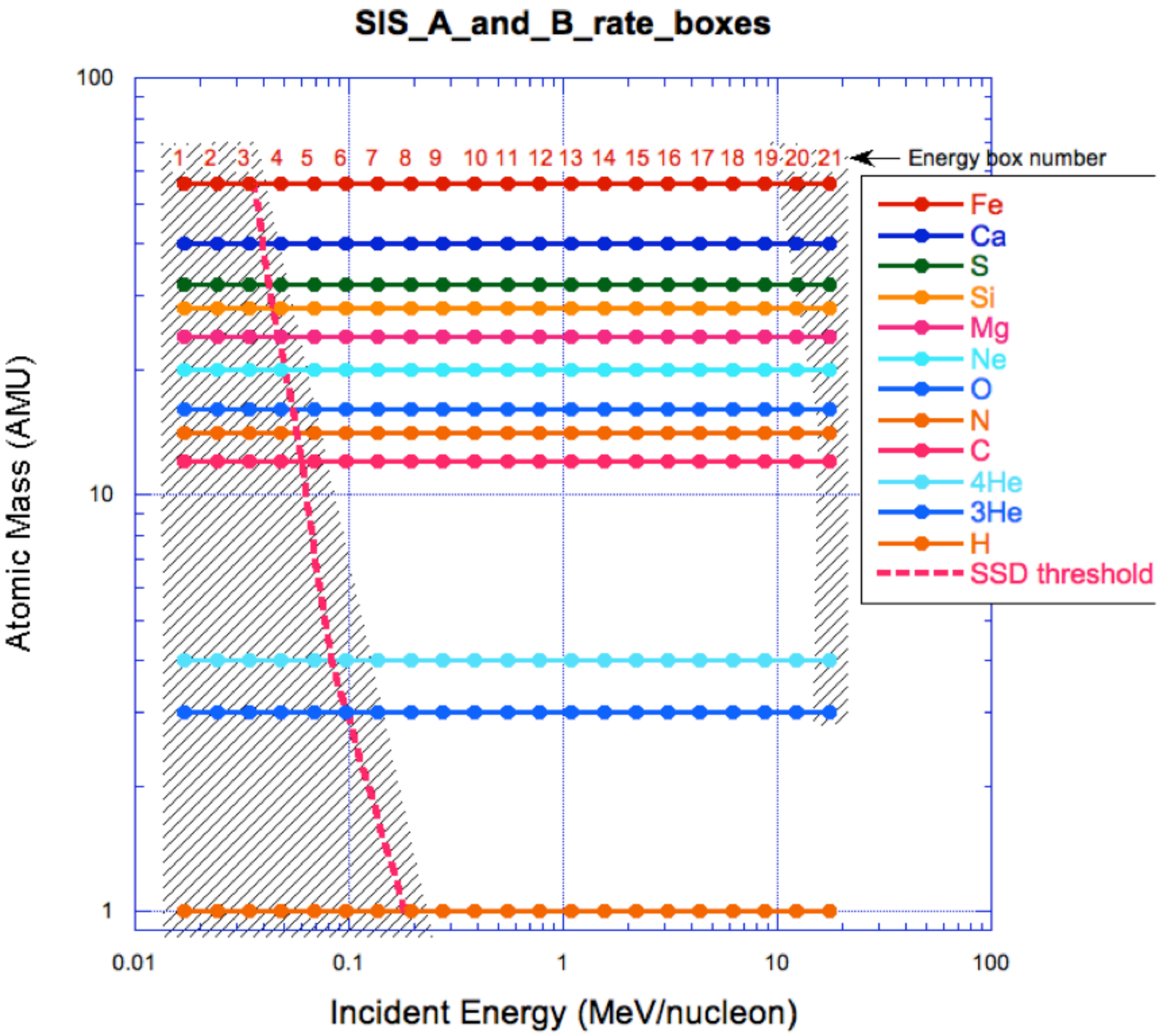






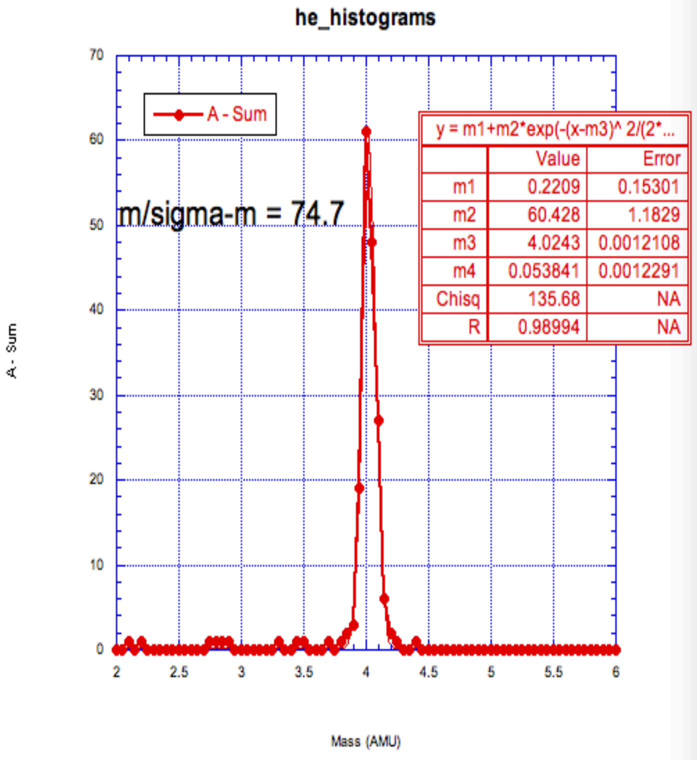


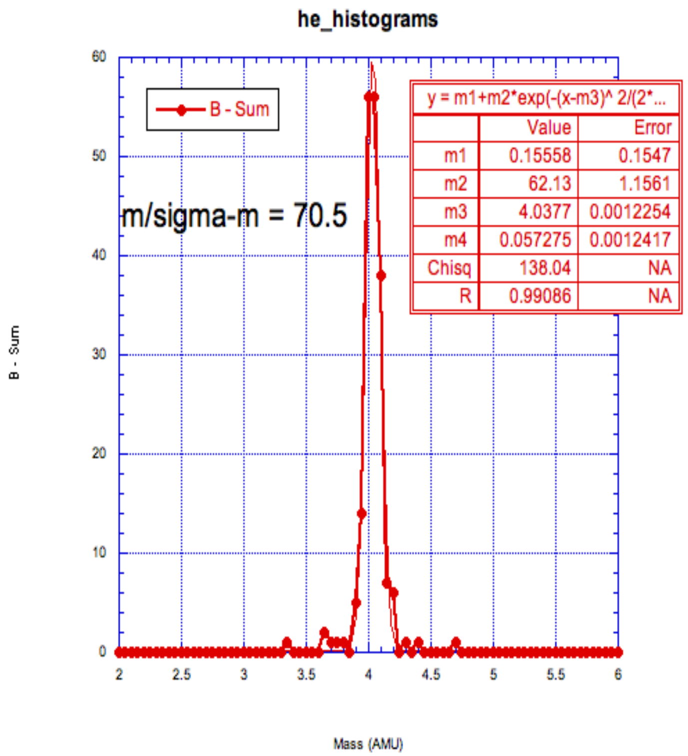
SIS Matrix Rate Box



Energy box #	Elo Incident energy (MeV/nucleon)	Ehi Incident energy (MeV/nucleon)	Eaverage (MeV/nucleon)
0	0.0141	0.0200	0.0171
1	0.0200	0.0283	0.0241
2	0.0283	0.0400	0.0341
3	0.0400	0.0566	0.0613
4	0.0566	0.0800	0.0683
5	0.0800	0.1131	0.0966
6	0.1131	0.1600	0.1366
7	0.1600	0.2263	0.1931
8	0.2263	0.3200	0.2731
9	0.3200	0.4525	0.3863
10	0.4525	0.6400	0.5463
11	0.6400	0.9051	0.7725
12	0.9051	1.2800	1.0925
13	1.2800	1.8102	1.5451
14	1.8102	2.5600	2.1851
15	2.5600	3.6204	3.0902
16	3.6204	5.1200	4.3702
17	5.1200	7.2408	6.1804
18	7.2408	10.2400	8.7404
19	10.2400	14.4815	12.3608
20	14.4815	20.4800	17.4807

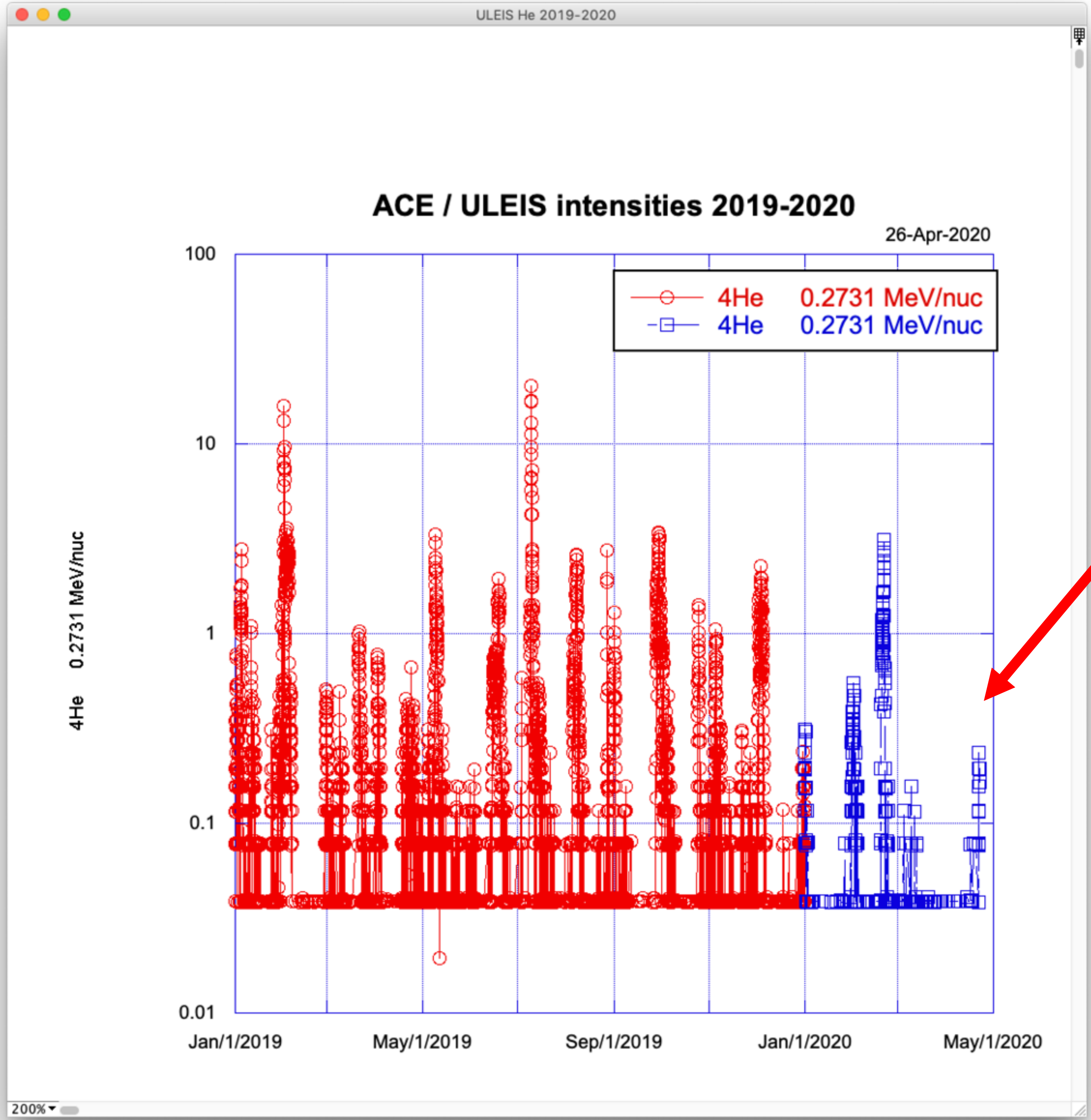
Helium Mass Histogram



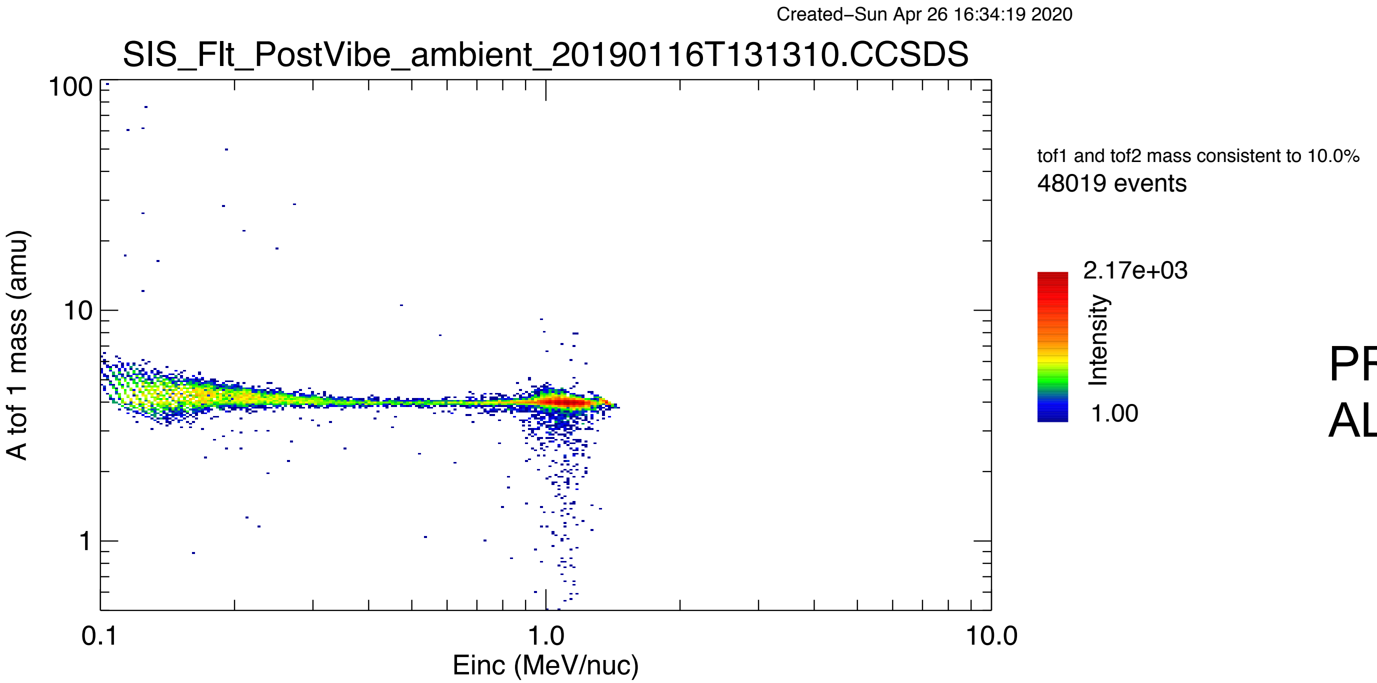


- Since the PHA telemetry is limited, this limits the timing resolution for $^3He/^4He$ ratio measurements.
- To help avoid this, He mass histograms are formed in the instrument allowing analysis of all the PHA events, not just the telemetered ones.
- The He mass histogram is:
  - mass range 2.0 - 6.0 AMU;
  - energy range 0.5 - 2.0 MeV/nuc

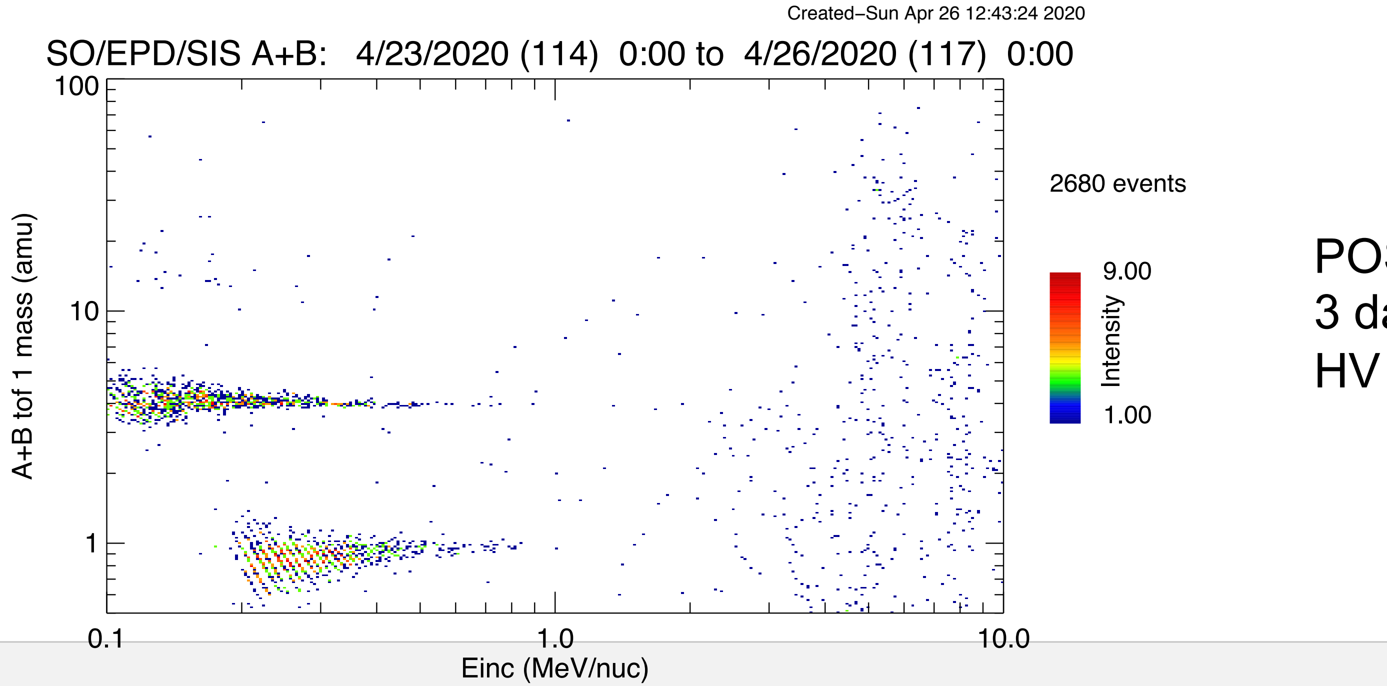
Launch: February 9 (10), 2020



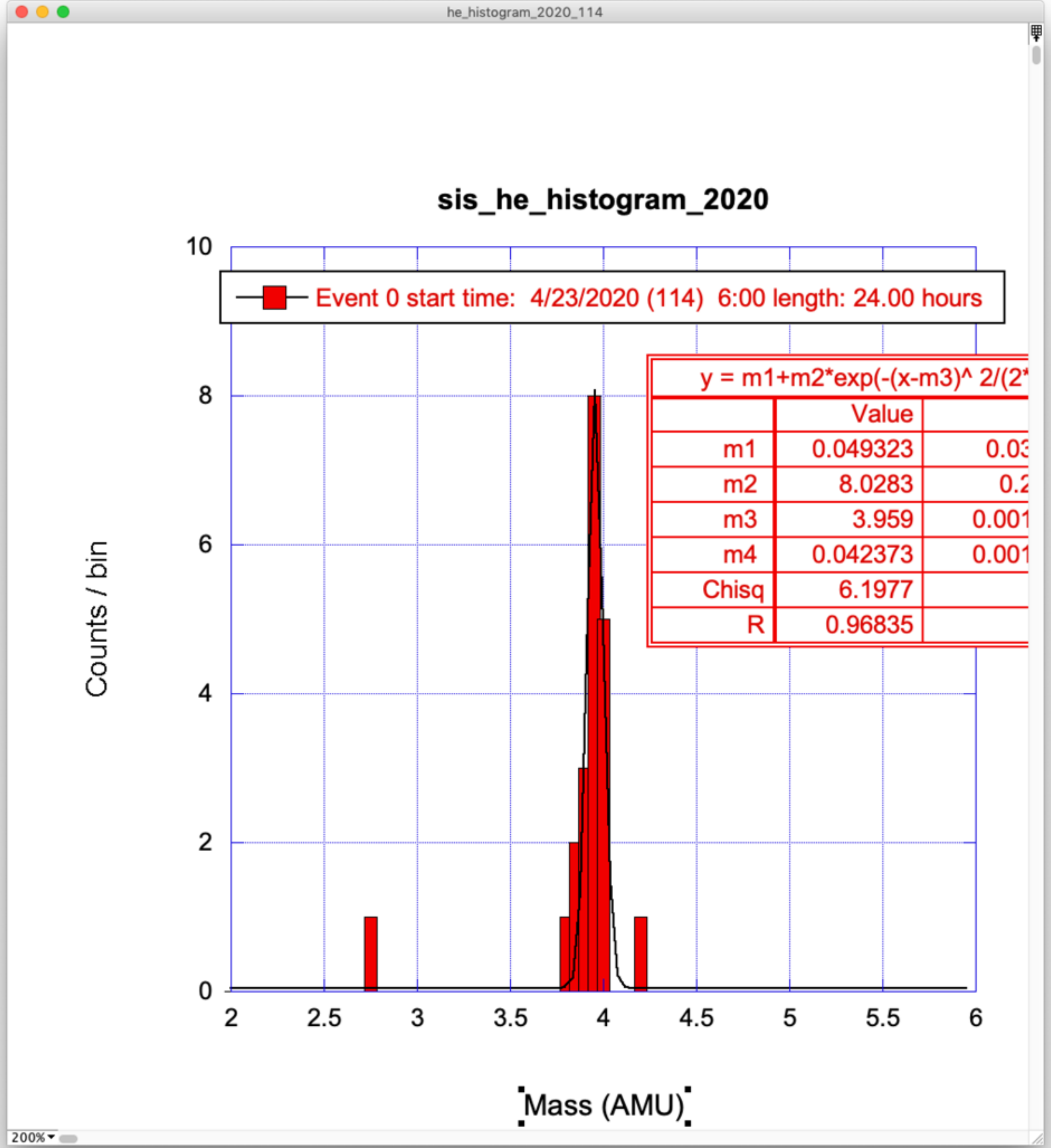
Energetic particle
Intensities very
Low right now



PRELAUNCH
ALPHA RUN



POST Launch
3 day sum after
HV ramp up

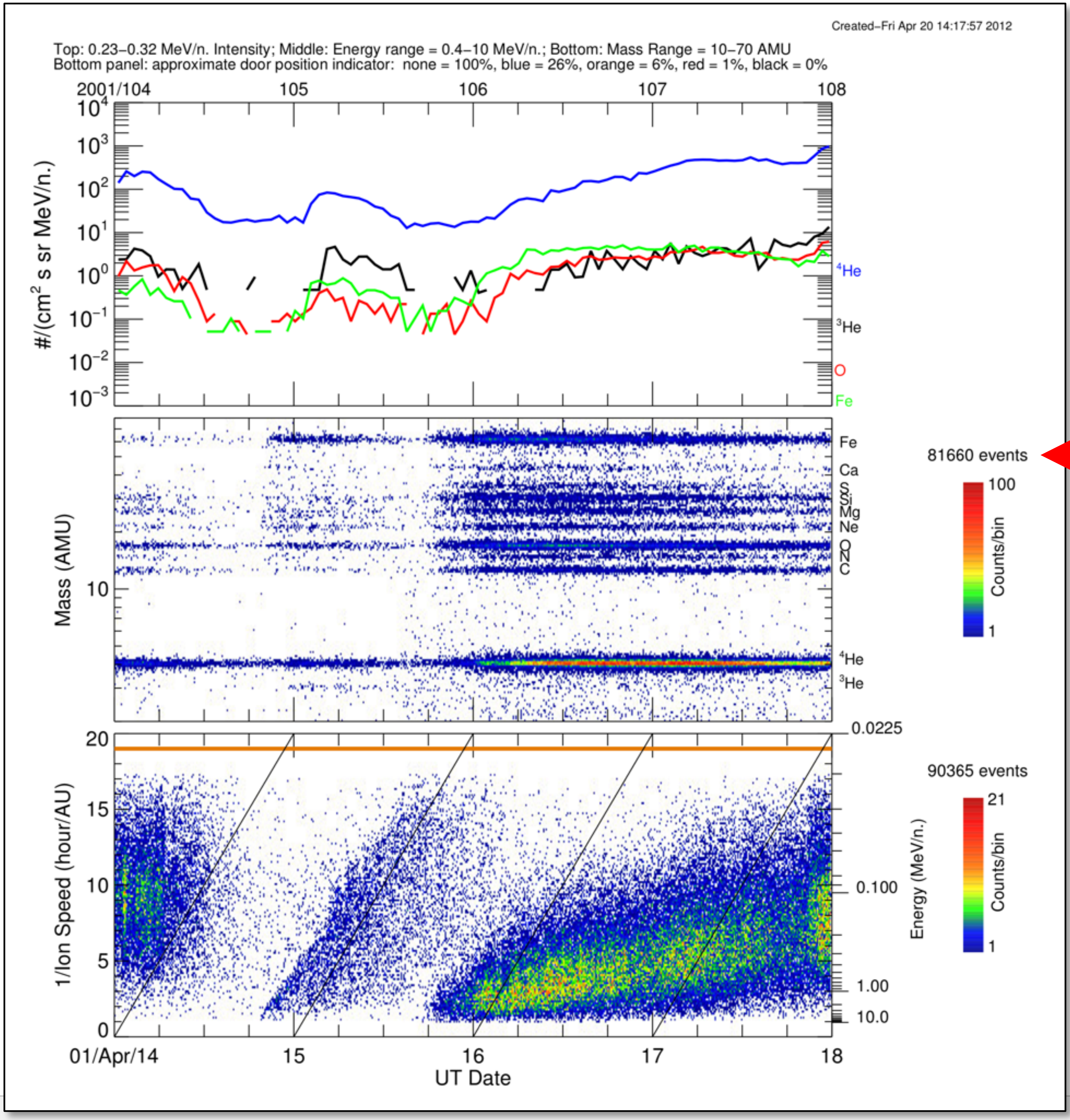


SIS He histogram

24 hour sum over Weak CIR

Most ions are near 0.5 MeV/nucleon

m/sigma-m = 3.959/0.0424 = 93.4 consistent With prelaunch Values and science Requirement (poor statistics)



Level 3 products are Higher level data, such As plots

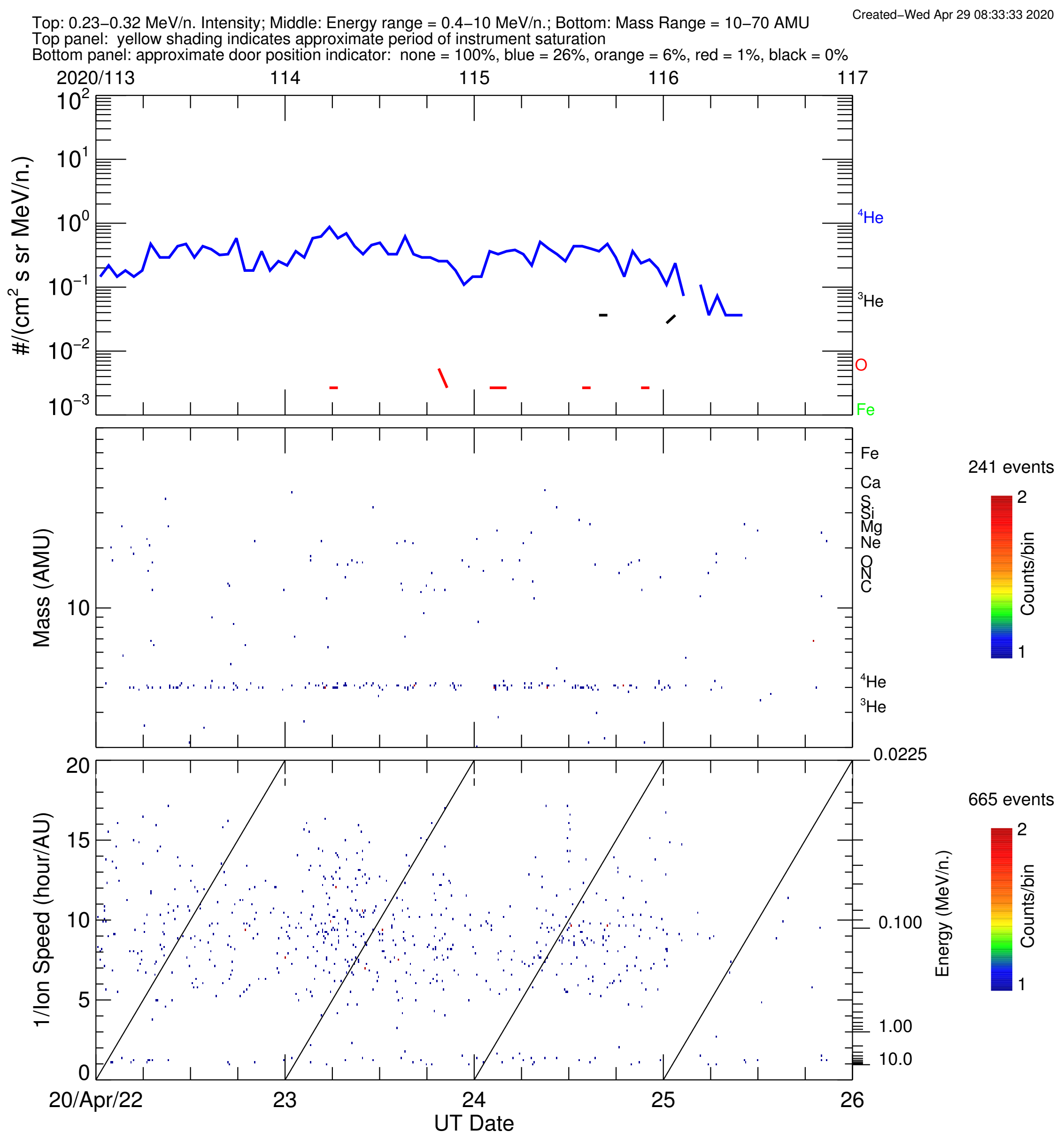
These will be developed by the EPD team in the Future

Example of plot from ACE/ULEIS posted at ACE Science Center – 4 day plots for entire Mission

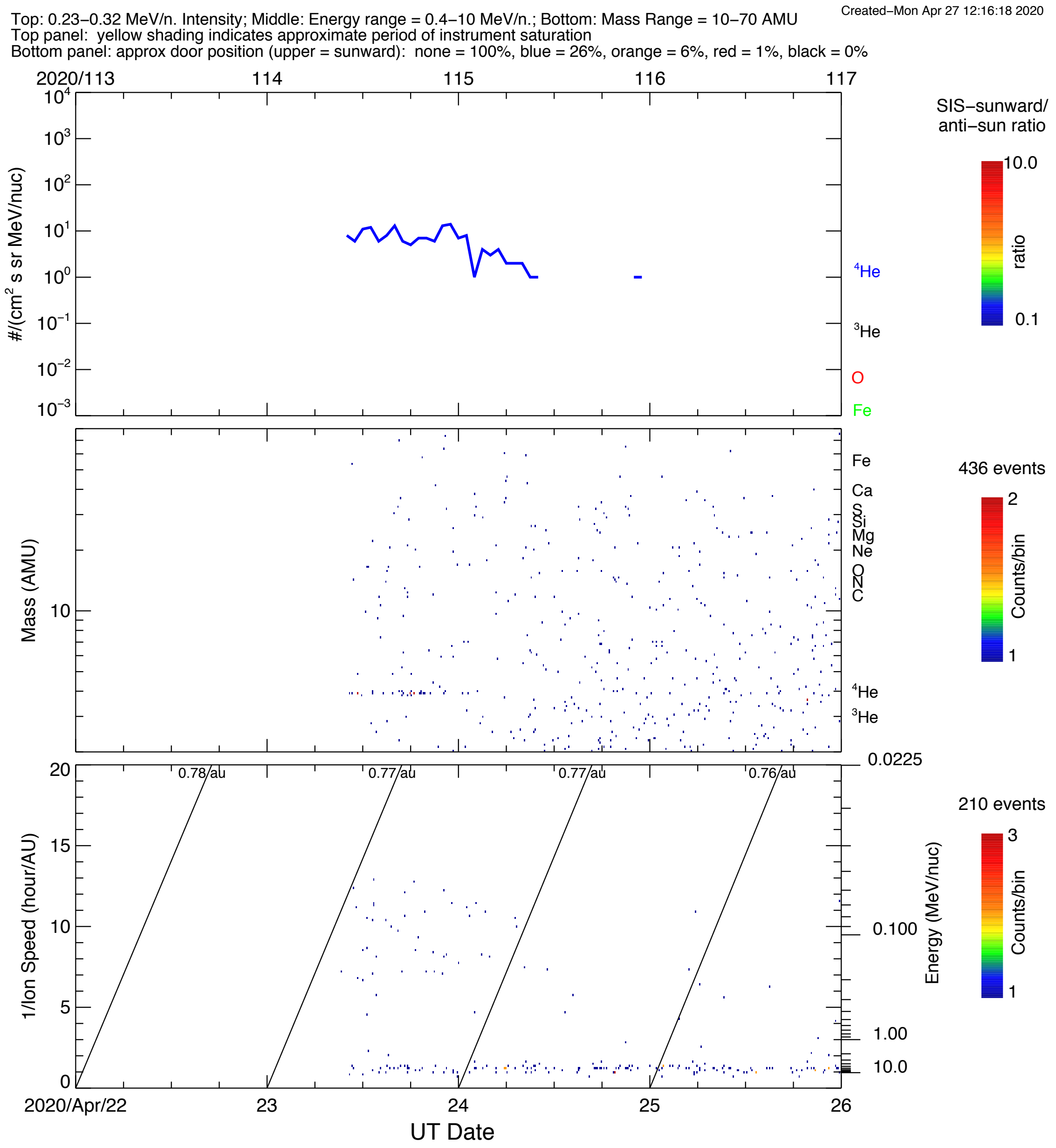
Shows impulsive, CME Related events during Period of high solar Activity

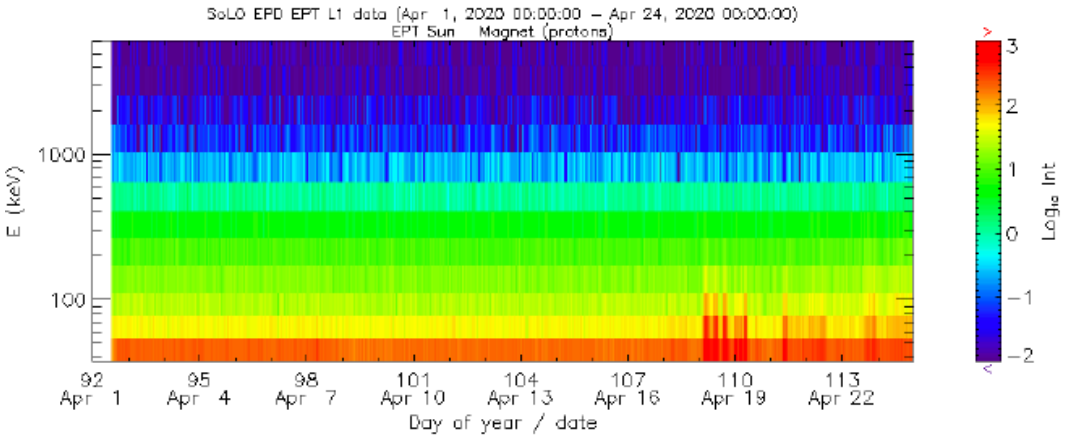
Similar plot planned For SO/EPD/SIS

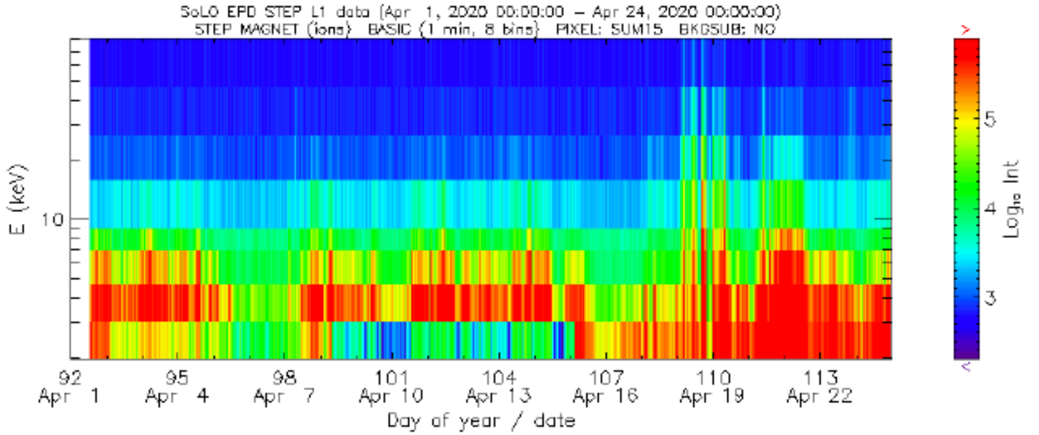
ACE/ULEIS

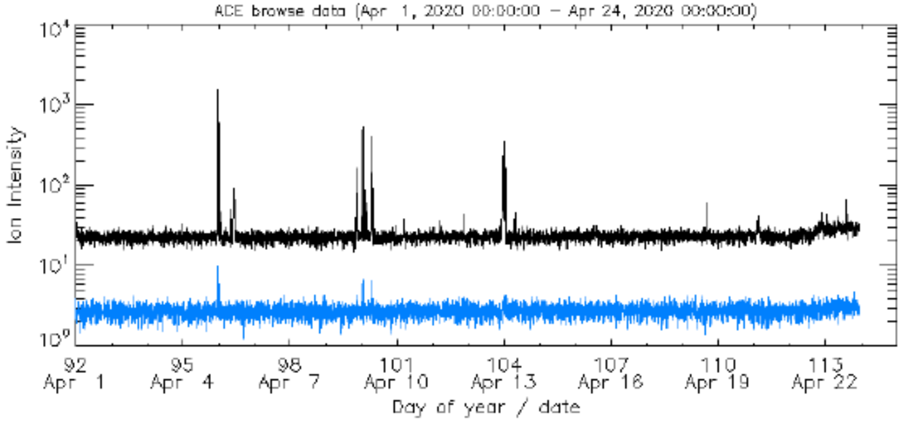


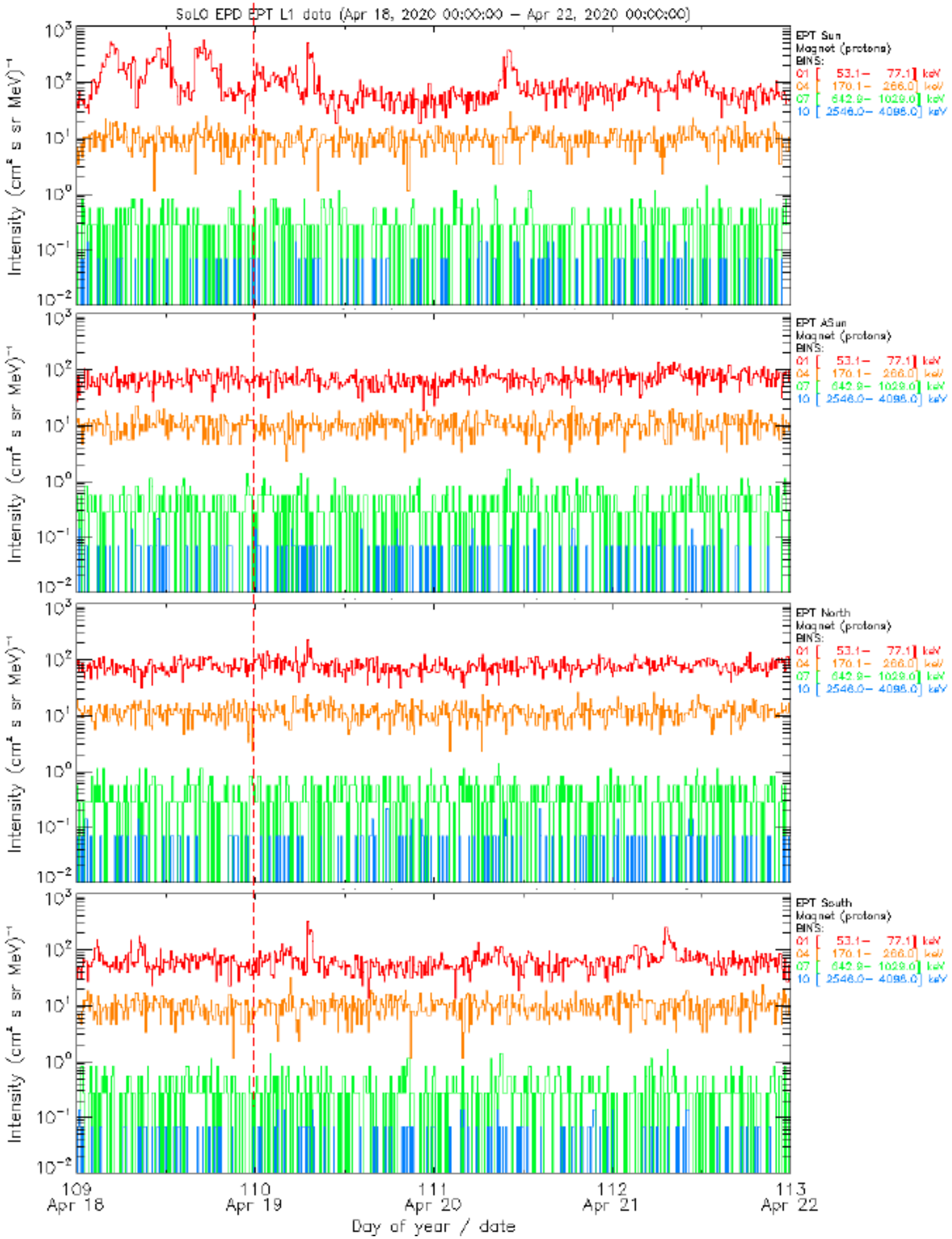
SO/SIS

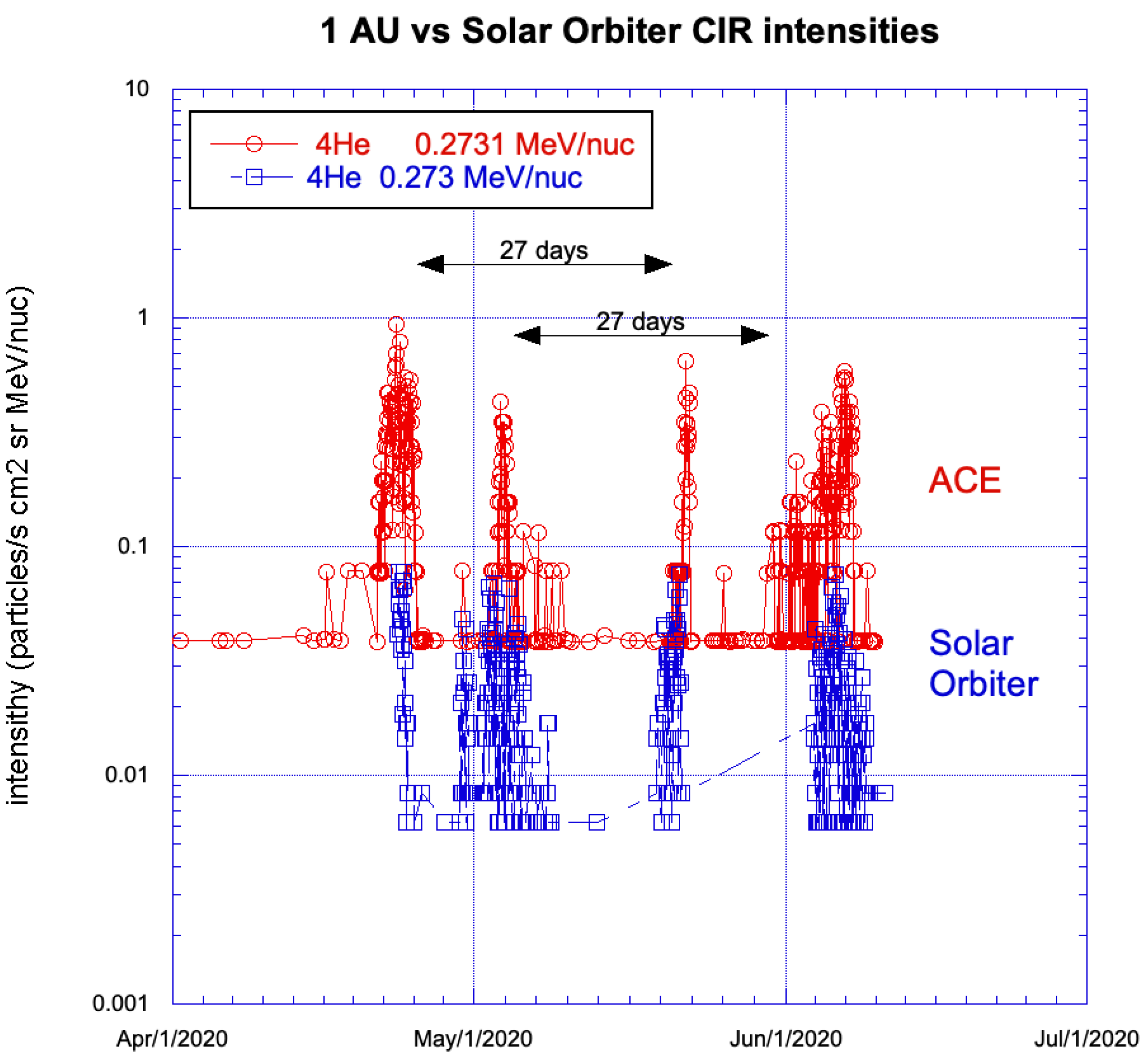



SoLO EPD EPT L1 data (Apr 1, 2020 00:00:00 – Apr 24, 2020 00:00:00)
EPT Sun Magnet (protons)
E (keV)
1000
100
Log₁₀ Int
92 Apr 1
95 Apr 4
98 Apr 7
101 Apr 10
104 Apr 13
107 Apr 16
110 Apr 19
113 Apr 22
Day of year / date


SoLO EPD STEP L1 data (Apr 1, 2020 00:00:00 – Apr 24, 2020 00:00:00)
STEP MAGNET (ions) BASIC (1 min, 8 bins) PIXEL: SUM15 BKGSUB: NO
E (keV)
10
Log₁₀ Int
92 Apr 1
95 Apr 4
98 Apr 7
101 Apr 10
104 Apr 13
107 Apr 16
110 Apr 19
113 Apr 22
Day of year / date


ACE browse data (Apr 1, 2020 00:00:00 – Apr 24, 2020 00:00:00)
Ion Intensity
92 Apr 1
95 Apr 4
98 Apr 7
101 Apr 10
104 Apr 13
107 Apr 16
110 Apr 19
113 Apr 22
Day of year / date


SoLO EPD EPT L1 data (Apr 18, 2020 00:00:00 – Apr 22, 2020 00:00:00)
EPT Sun
EPT ASun
EPT North
EPT South
Magnet (protons)
BINS:
Intensity (cm² s sr MeV)⁻¹
109 Apr 18
110 Apr 19
111 Apr 20
112 Apr 21
113 Apr 22
Day of year / date



1 AU vs Solar Orbiter CIR intensities
4He 0.2731 MeV/nuc
4He 0.273 MeV/nuc
27 days
27 days
ACE
Solar Orbiter
intensithy (particles/s cm2 sr MeV/nuc)
10
1
0.1
0.01
0.001
Apr/1/2020
May/1/2020
Jun/1/2020
Jul/1/2020

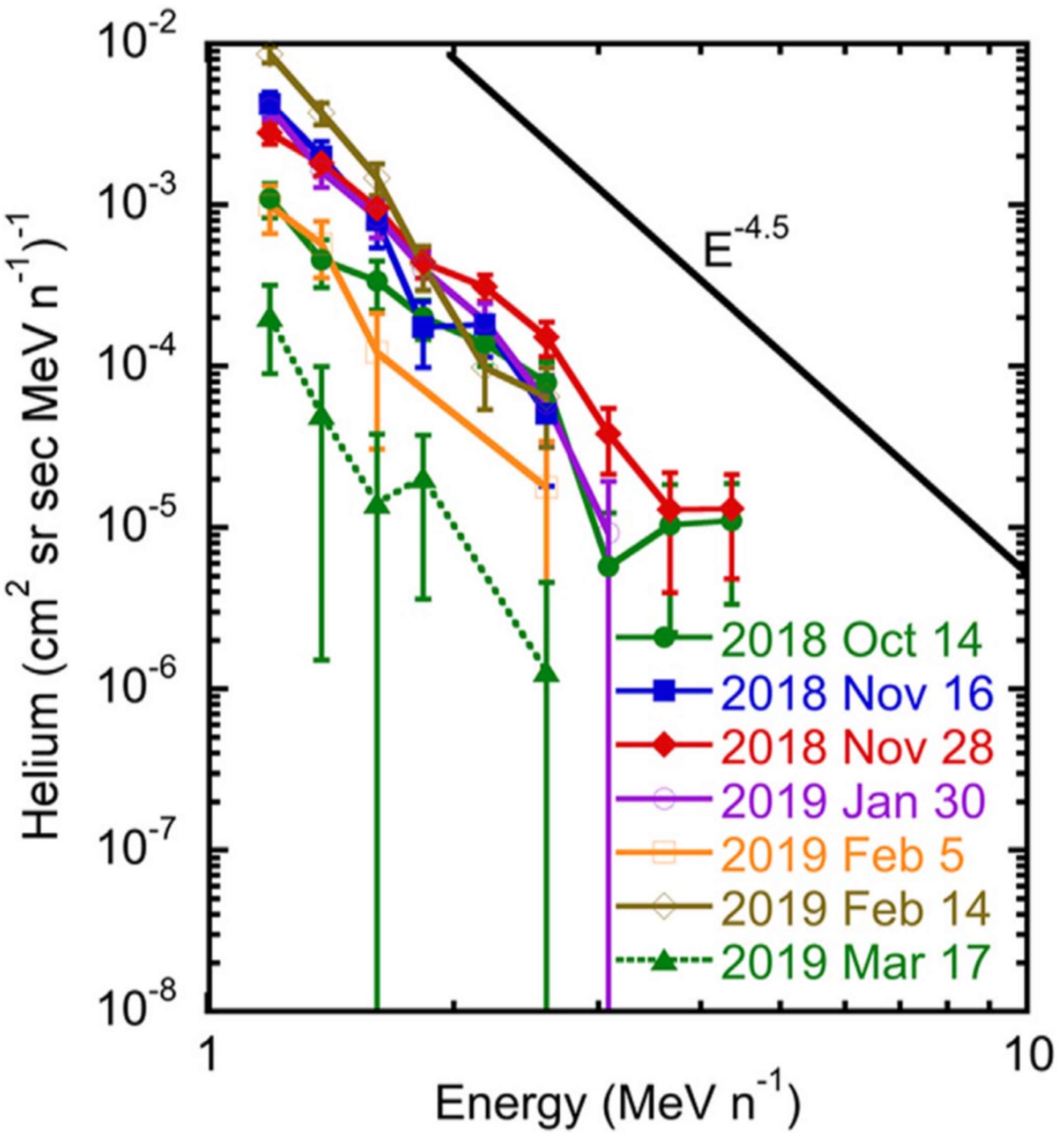


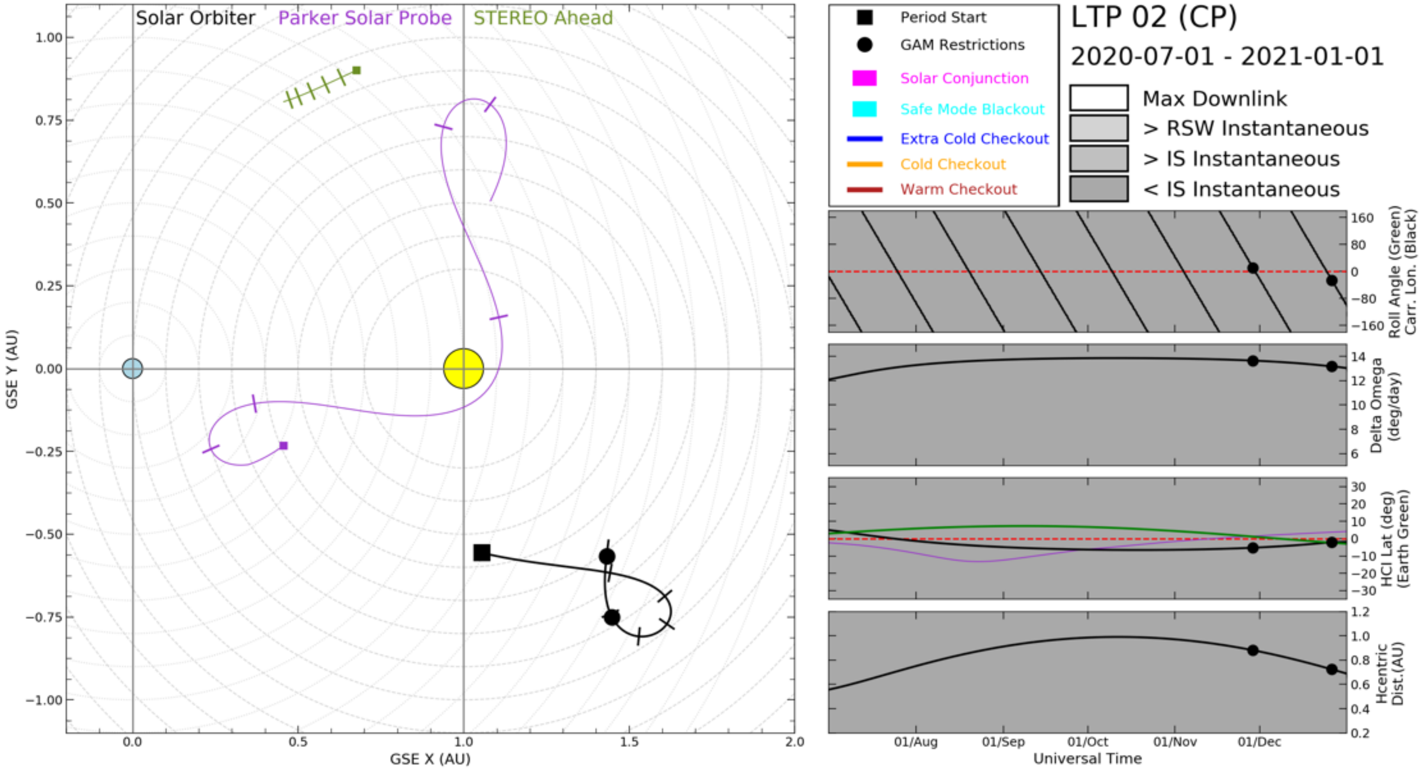
Figure 5. Time-integrated helium spectra (from the average of LETA and LETB He spectra) for all seven events. A line corresponding to an $E^{-4.5}$ power law is shown for reference.

PSP CIR He spectra

Cohen et al,
ApJ. V246, 2020.

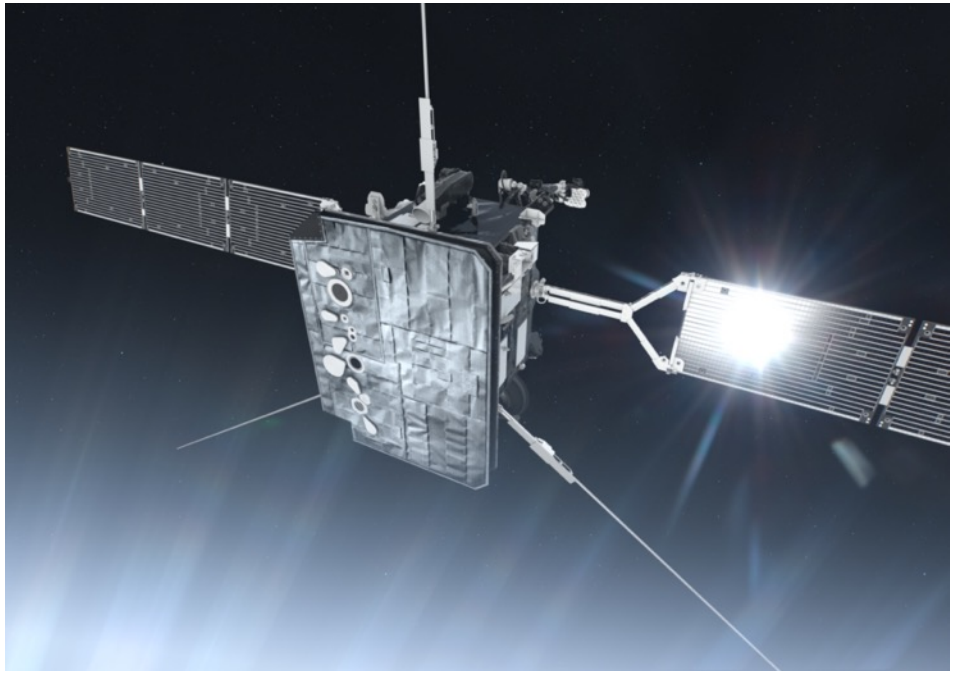
Solar Orbiter Current Status

- The mission just transitioned from Commissioning to Cruise Phrase operation
- All in-situ instruments will be taking continuous measurement
- Remote Checkout Windows
  - June 2020
  - Feb, Mar, Sep 2021
- Venus Gravity Assist #1
  - Dec 2020
- Go Solar Orbiter !



JOHNS HOPKINS

APPLIED PHYSICS LABORATORY



solar orbiter