Energetic particle observations in the inner heliosphere

Past, Present and Future

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ECRS2010, Turku
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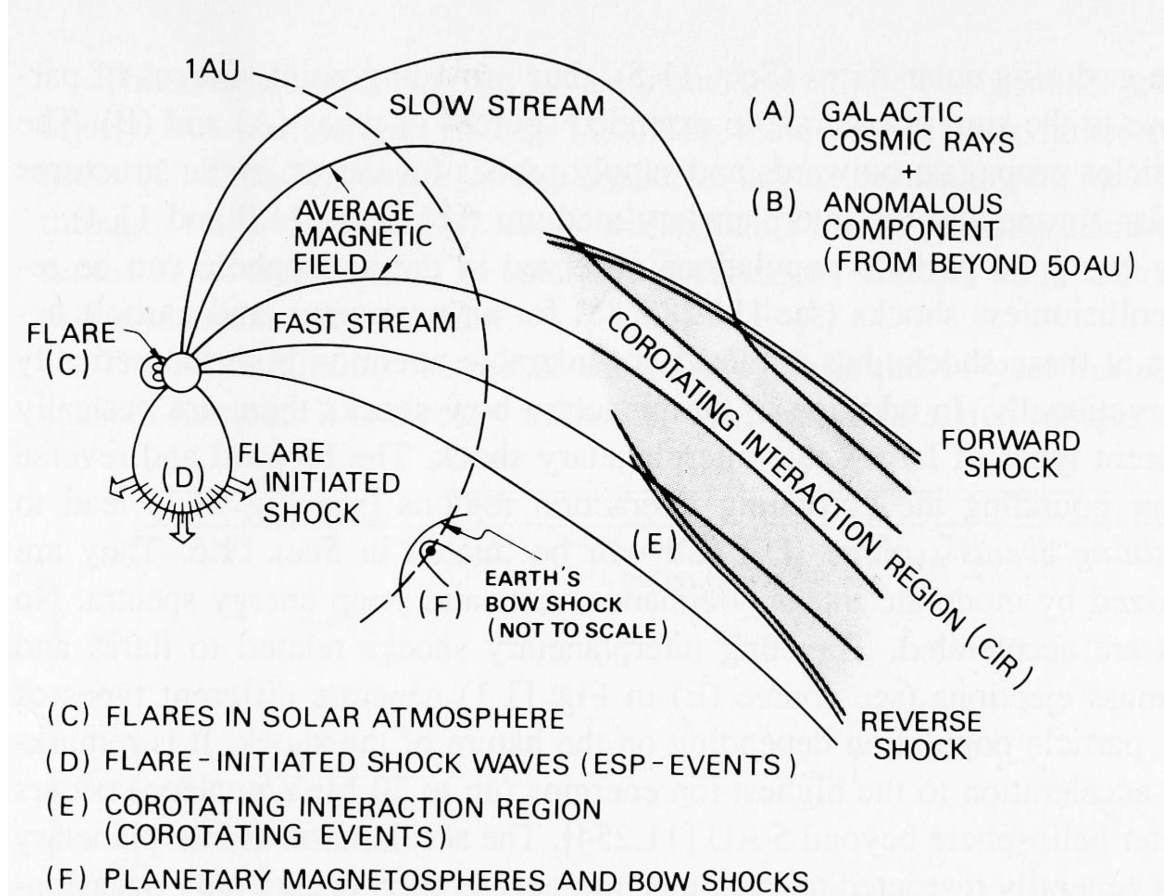
OUTLINE

1. Background
    a. Energetic particle populations
    b. The Big Questions
2. What have we learnt from past missions to the *inner* heliosphere?
    a. Mariner 10
    b. Helios 1 & 2
3. Current knowledge (and open questions)
4. Future prospects
    a. Messenger
    b. BepiColombo
    c. Solar Orbiter
    d. Solar Probe Plus
5. Summary

ENERGETIC PARTICLE POPULATIONS

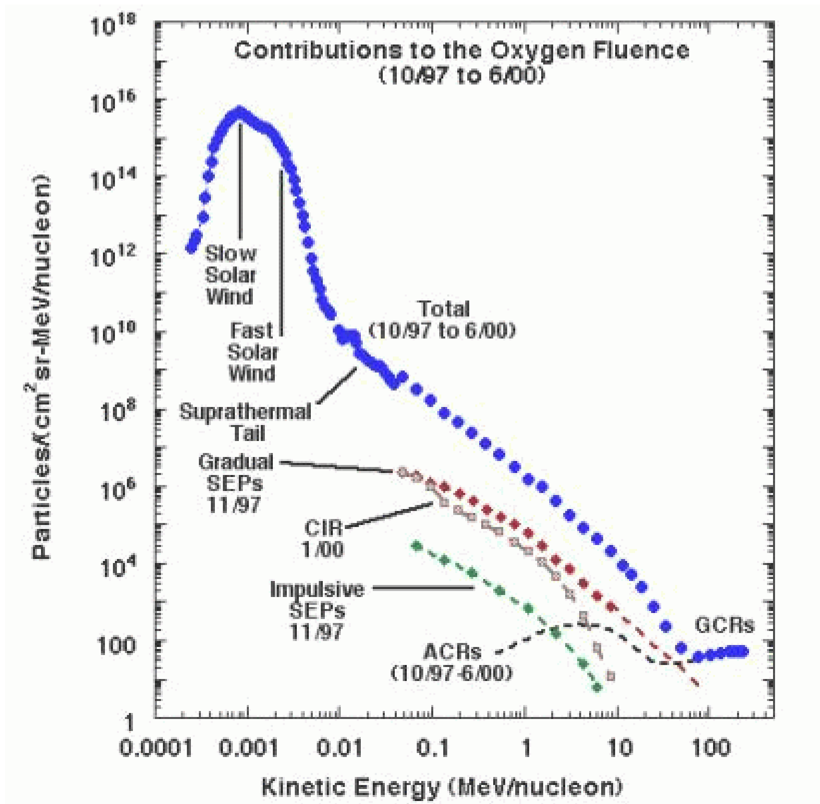
A. Galactic cosmic rays
B. Anomalous Cosmic Ray (ACR) component
C. **Flare-accelerated Solar Energetic Particles (SEP)**
D. **(CME-driven) shock-accelerated SEP**
E. **Corotating events**
F. **Magnetospheric particles (e.g. Jovian electrons)**



Kunow et al., 1991

THE BIG QUESTIONS

What are the sources, acceleration mechanisms, and transport processes of energetic particles in the heliosphere?

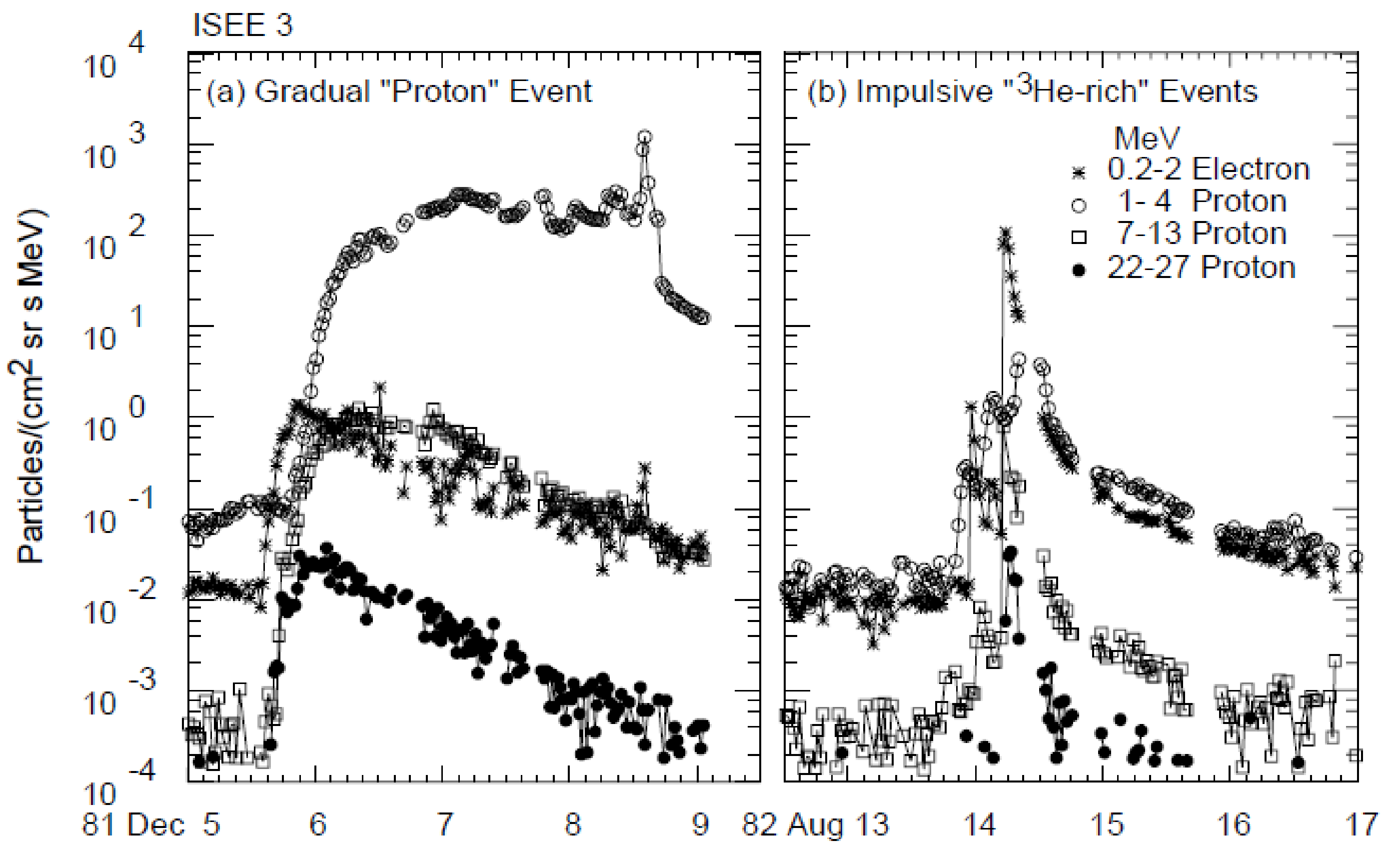


SEP EVENT CLASSIFICATION

Prior to Solar Cycle 23:

2 SEP Event Classes:

- "Gradual" and "Impulsive"
- Terminology taken from associated X-ray event classification
- "Reames Paradigm":
  - Particles in Gradual events are CME shock-accelerated
  - Particles in Impulsive events are flare-accelerated



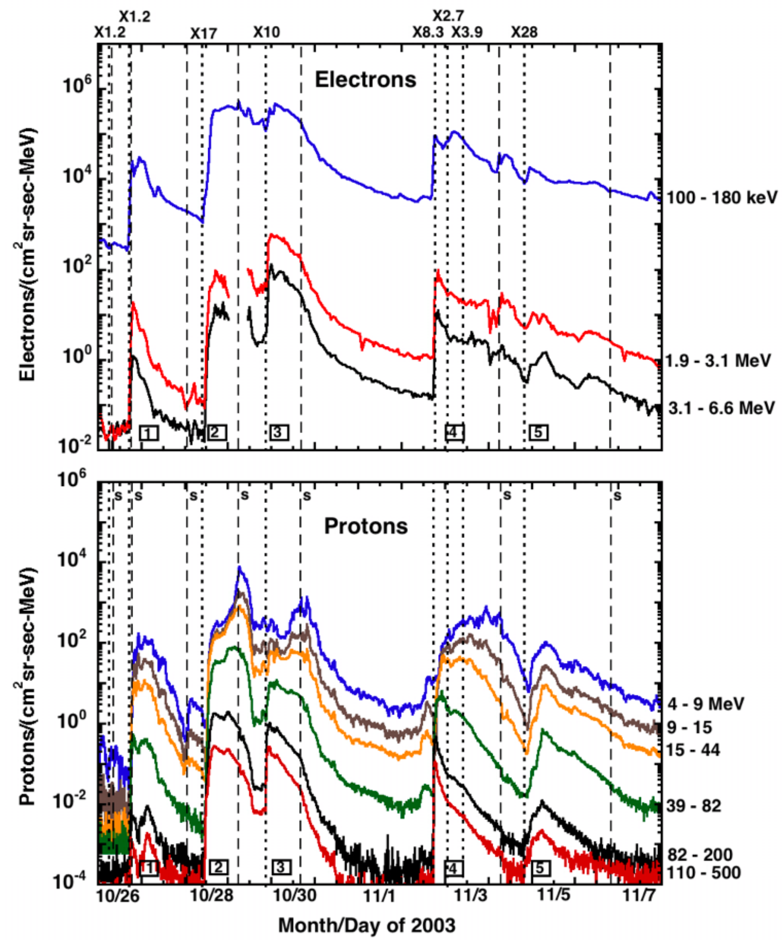
Reames, 1999

SEP EVENT CLASSIFICATION

Gradual Events

- proton-rich (e/p ratio small)
- variable composition and charge states
  - $^3He/^4He$ (>) ~0.0005
  - Fe/O ~0.1 (0.01-1.0)
  - Q_{Fe} (>)~14
- >~100° in solar longitude
- associated with gradual X-ray flares and fast coronal mass ejections (CMEs)
- believed to be due to acceleration by CME-driven shocks
- Duration ~days
- ≈ 1/month at Solar Max.

"Halloween Storms"



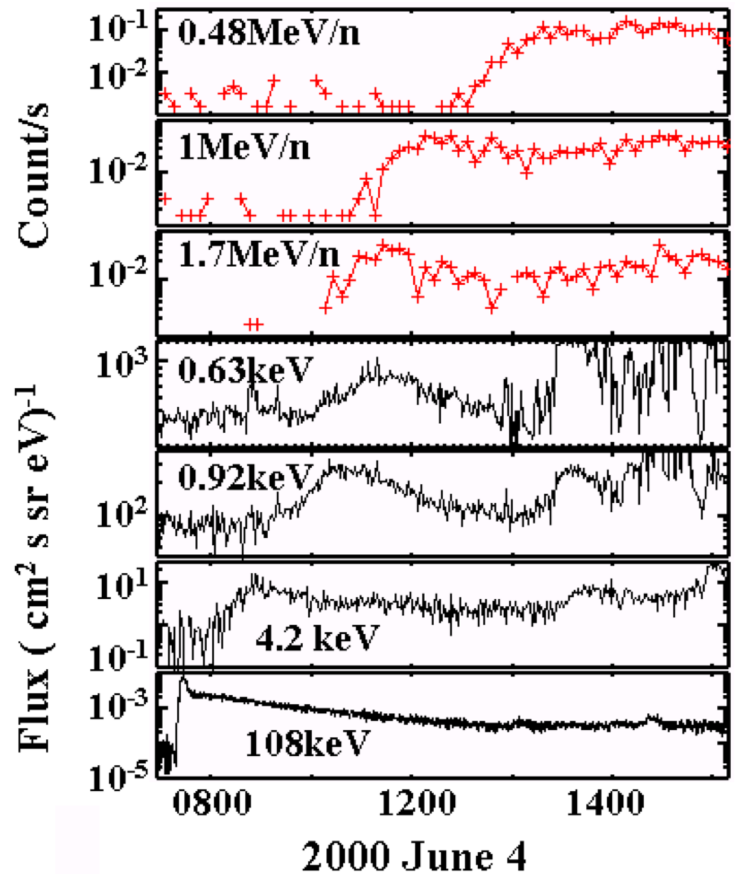
Mewaldt et al., 2005

SEP EVENT CLASSIFICATION

esa

Impulsive Events

- electron-rich (e/p ratio large)
- variable composition and charge states
  - $^3He/^4He \sim 1$
  - $Fe/O \sim 1$
  - $Q_{Fe} \sim 20$
- $\sim 30^\circ$ in solar longitude
- associated with impulsive X-ray flares, type III radio bursts and often with CMEs
- believed to be due to acceleration in flares
- Duration ~hours
- ≈ 1000/month at Solar Max.



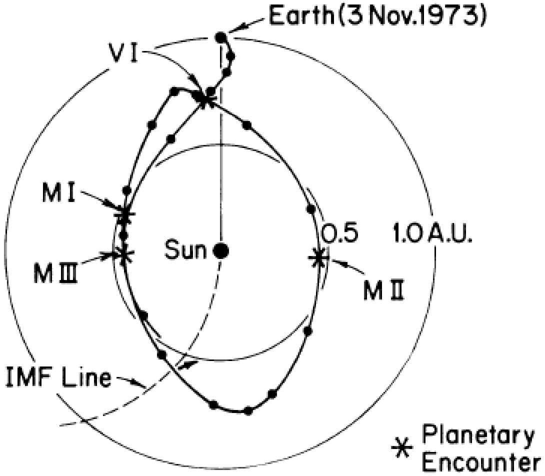
Energetic particle observations in the inner heliosphere

Past, Present and Future

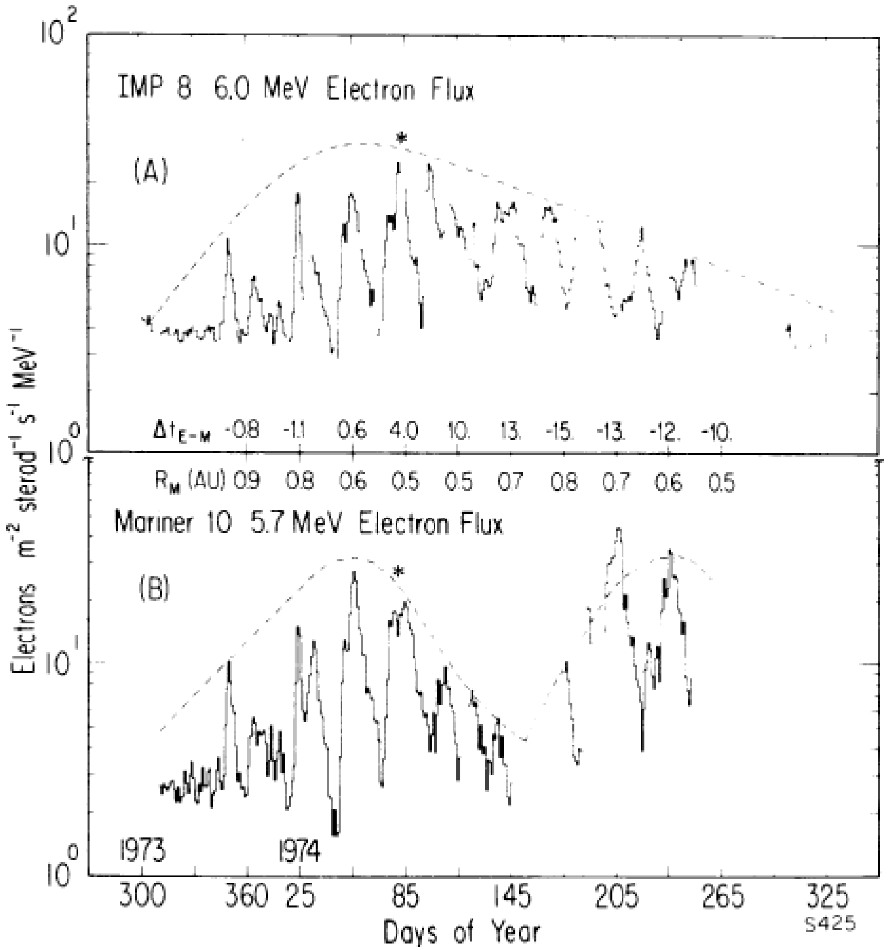
PAST MISSIONS < 1 AU

Mariner 10

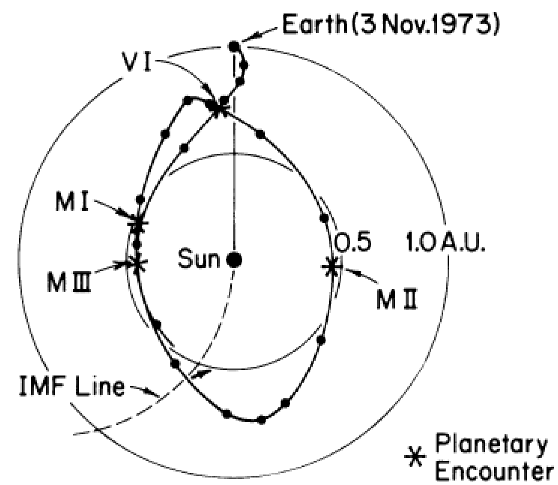
- Launch date: 1973-11-03
- Mercury fly-bys:
    - 1974-03-29
    - 1974-09-21
    - 1975-03-16
- Key results:
    - Jovian electrons observed at ≤0.5 AU
        - Radial gradients:
        - varied from -140 to +140 %/AU



PAST MISSIONS < 1 AU

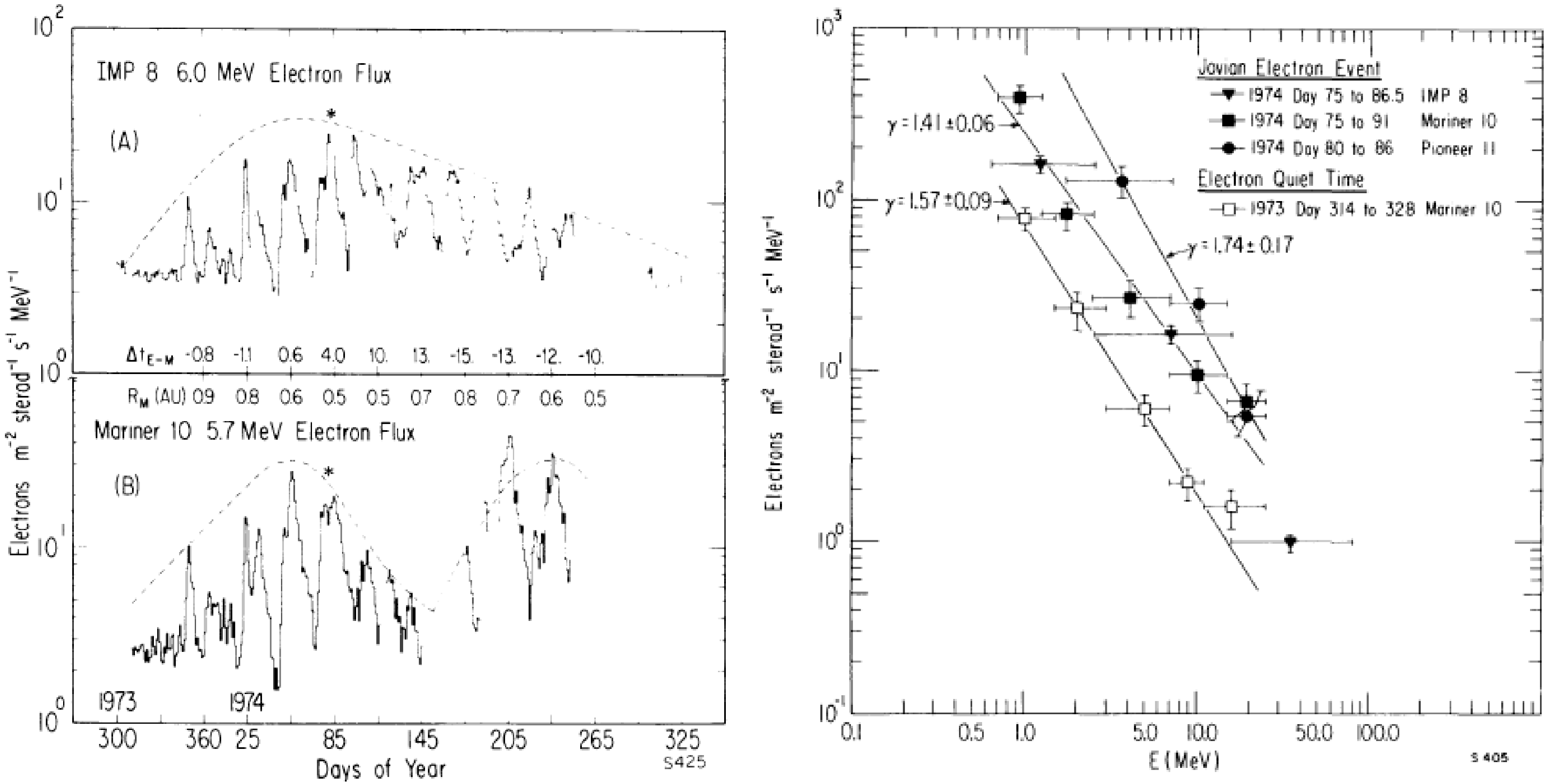


Eraker & Simpson, 1979



European Space Agency

PAST MISSIONS < 1 AU

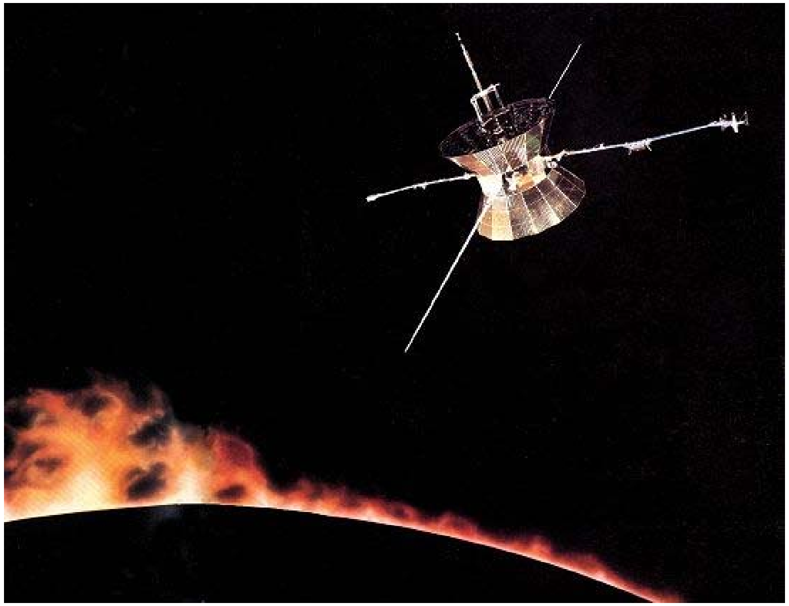


Eraker & Simpson, 1979

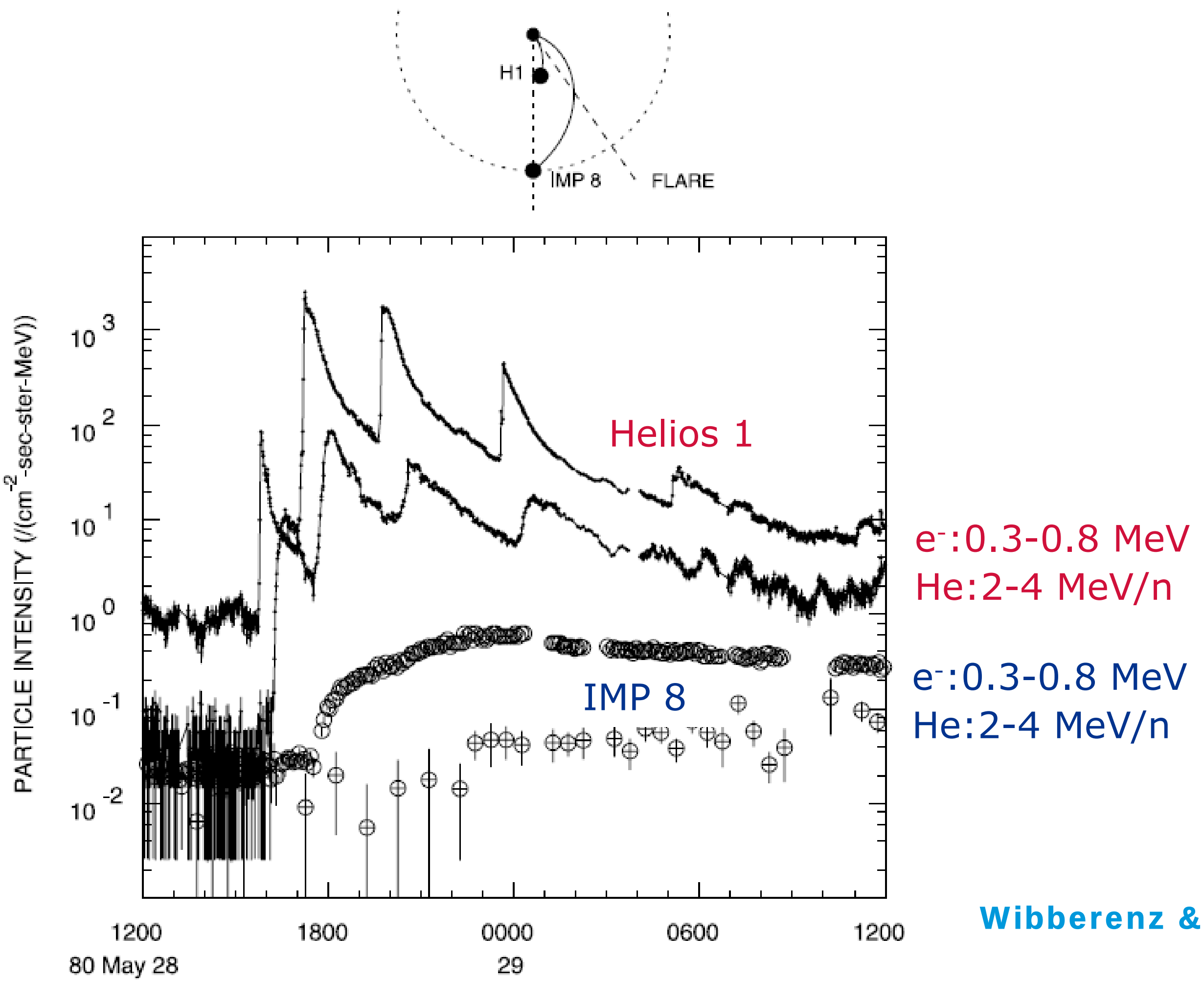
PAST MISSIONS < 1 AU

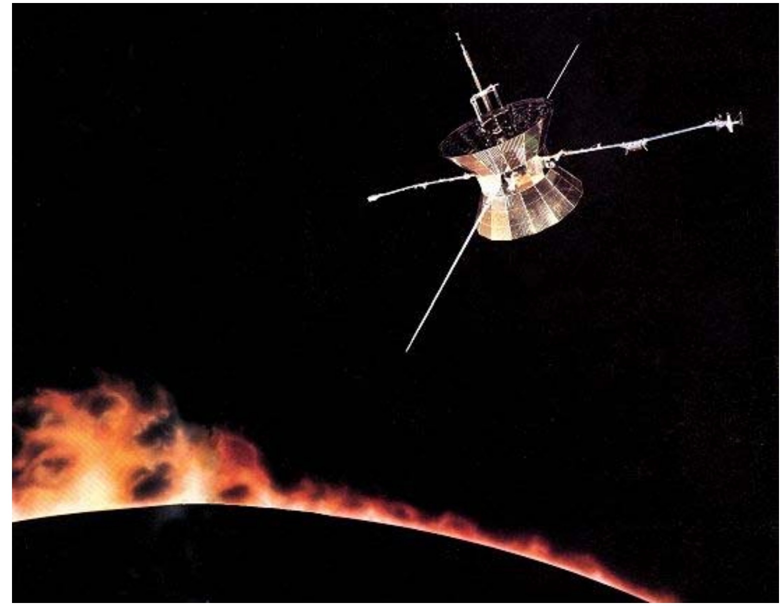
Helios 1 & 2

- Launch Date:
  - 1974-12-10 (H1); 1976-01-15 (H2)
- Key results:
  - Multi-spacecraft observations 0.29-1.0 AU
  - 3He-rich events
  - Radial gradients
  - ……



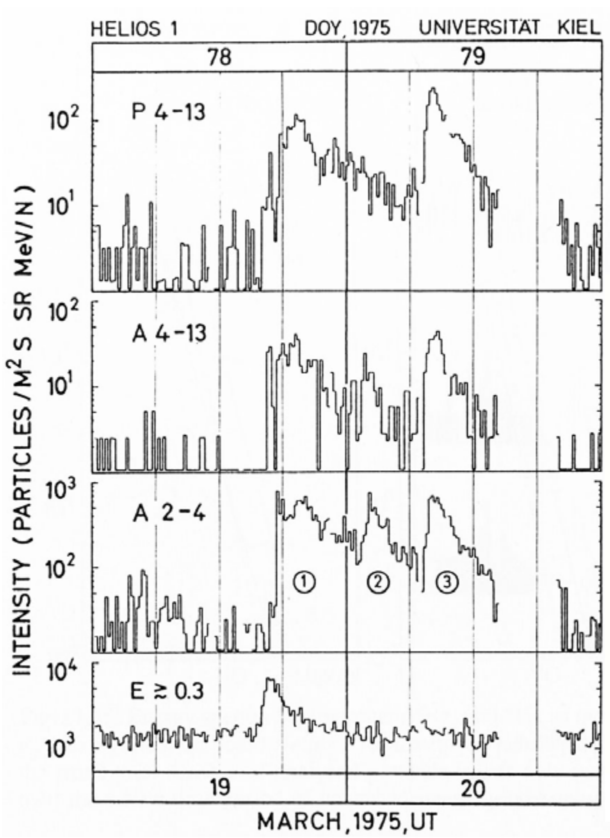
PAST MISSIONS < 1 AU



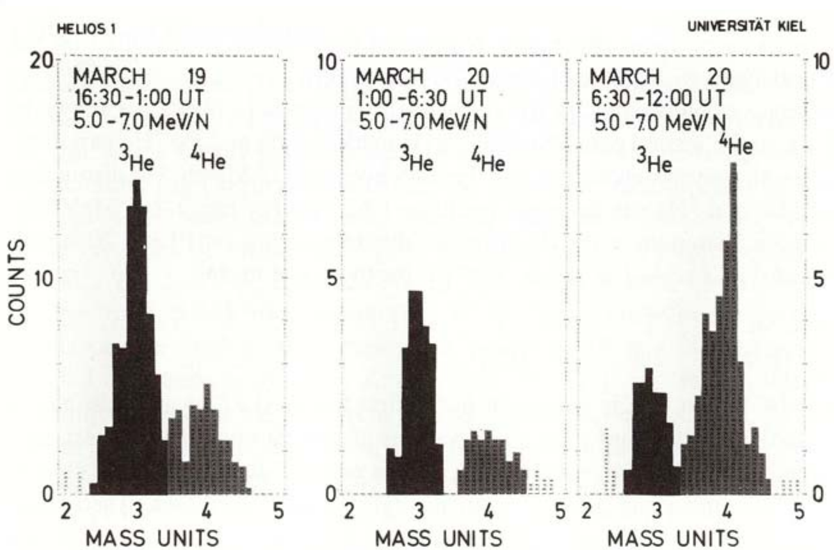


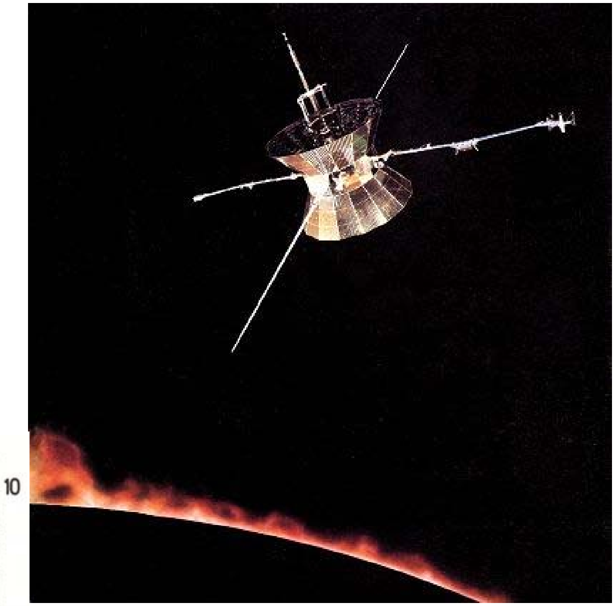
Wibberenz & Cane, 2006

PAST MISSIONS < 1 AU



^{3}He-rich events at 0.35 AU





Kunow, 1978

Energetic particle observations in the inner heliosphere

Past, **Present** and Future

KEY SEP QUESTIONS

1. How are particles accelerated continuously at the Sun and in the inner heliosphere?

2. What seed populations and conditions close to the Sun determine which CME-driven shocks will accelerate particles to high energies?

3. What contributions do flare and shock-accelerated particles make to large solar particle events?

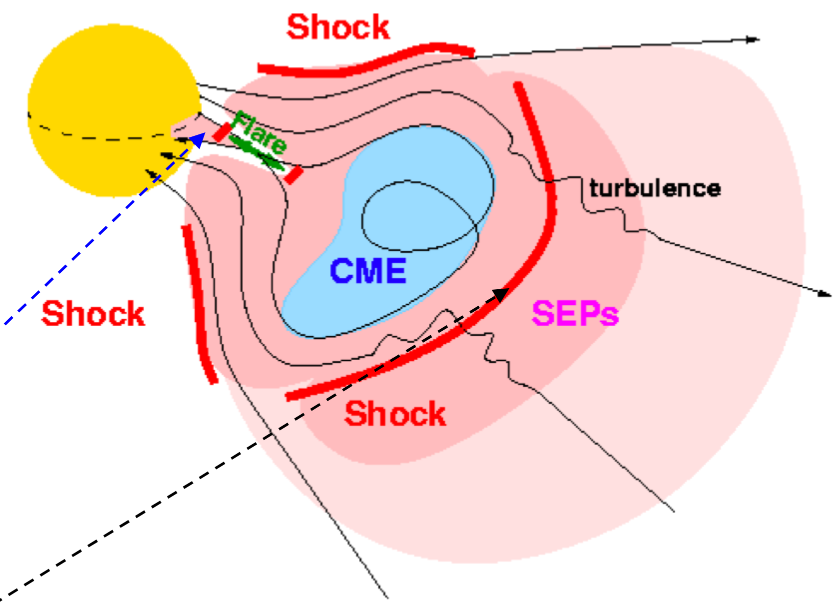
4. How to solar energetic particles escape from the Sun and get transported to 1 AU and beyond?

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

How are particles accelerated continuously at the Sun and in the inner heliosphere?

<u>Samples of acceleration processes</u>:

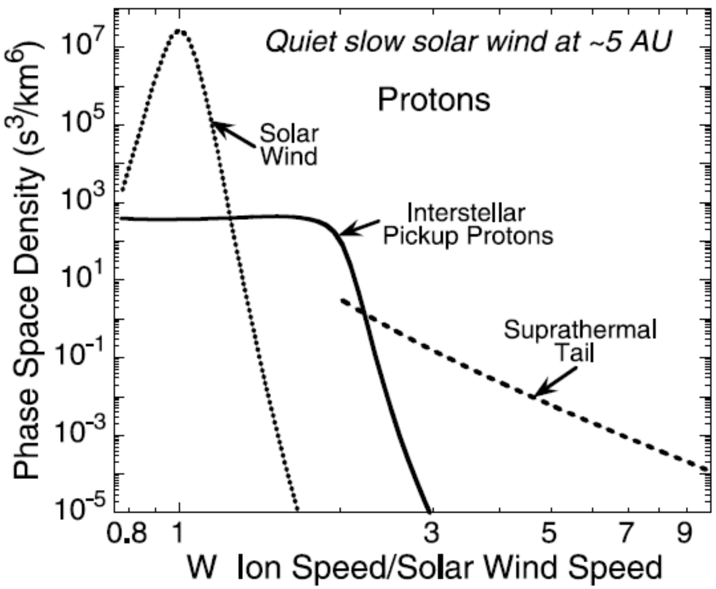
- resonant wave-particle interactions
- turbulence
- magnetic reconnection
- quasi-static electric fields
- diffusive shock acceleration
- shock drift and shock surfing
- etc.

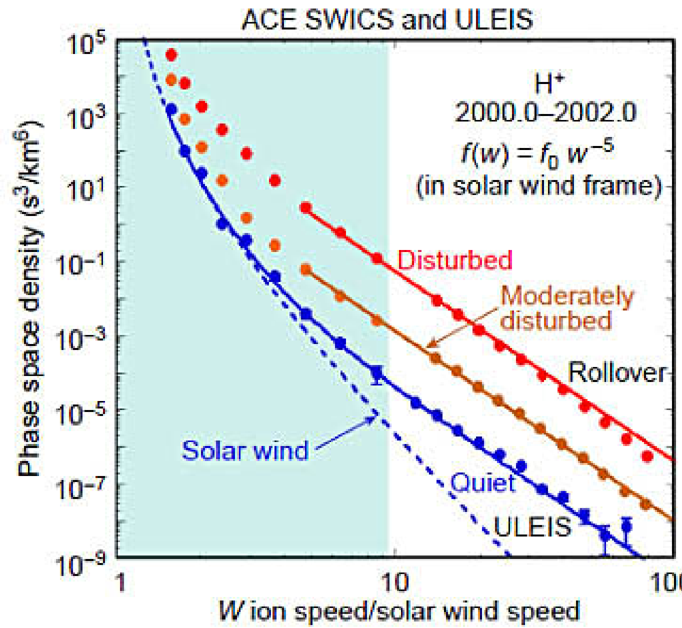


After Rodriguez-Pacheco et al., 2009

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

How are particles accelerated continuously at the Sun and in the inner heliosphere?





After Gloeckler, 2003

All solar wind species develop suprathermal tails somewhere between the Sun and 1 AU that extend to >100 keV/nuc.

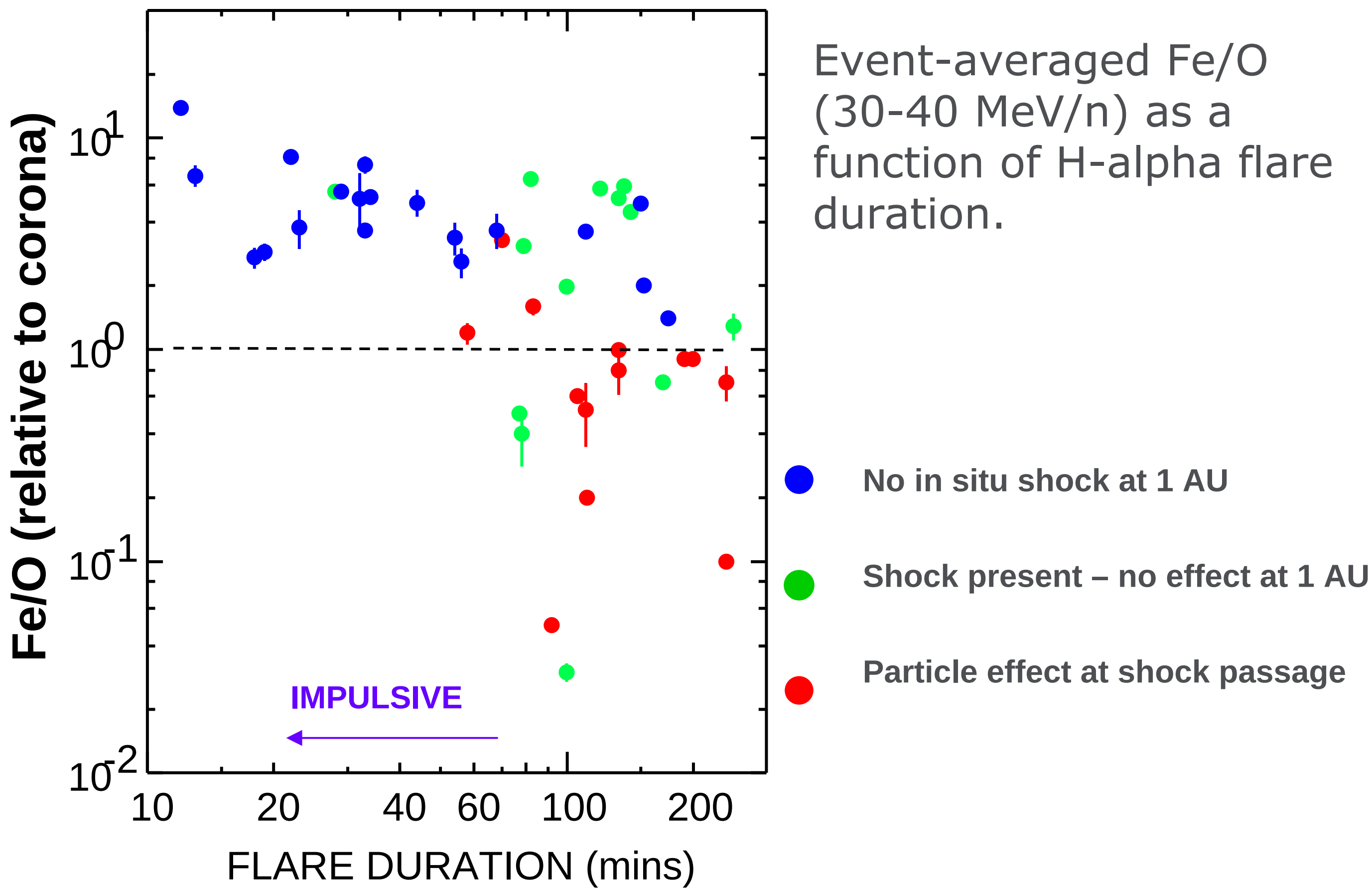
- common spectral shape: power law with spectral index of −5 (−1.5 when the spectrum is expressed as differential intensity).
- acceleration mechanism: likely to be stochastic acceleration in compressional turbulence. (Fisk and Gloeckler, 2007)

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

What contributions do flare and shock-accelerated particles make to large solar particle events?

Recent observations show that many (large) SEP events have heavy ion enhancements typical of "impulsive" events

Do Fe-rich SEP events include directly-accelerated flare particles?



Event-averaged Fe/O (30-40 MeV/n) as a function of H-alpha flare duration.

Cane et al., 2002,2003

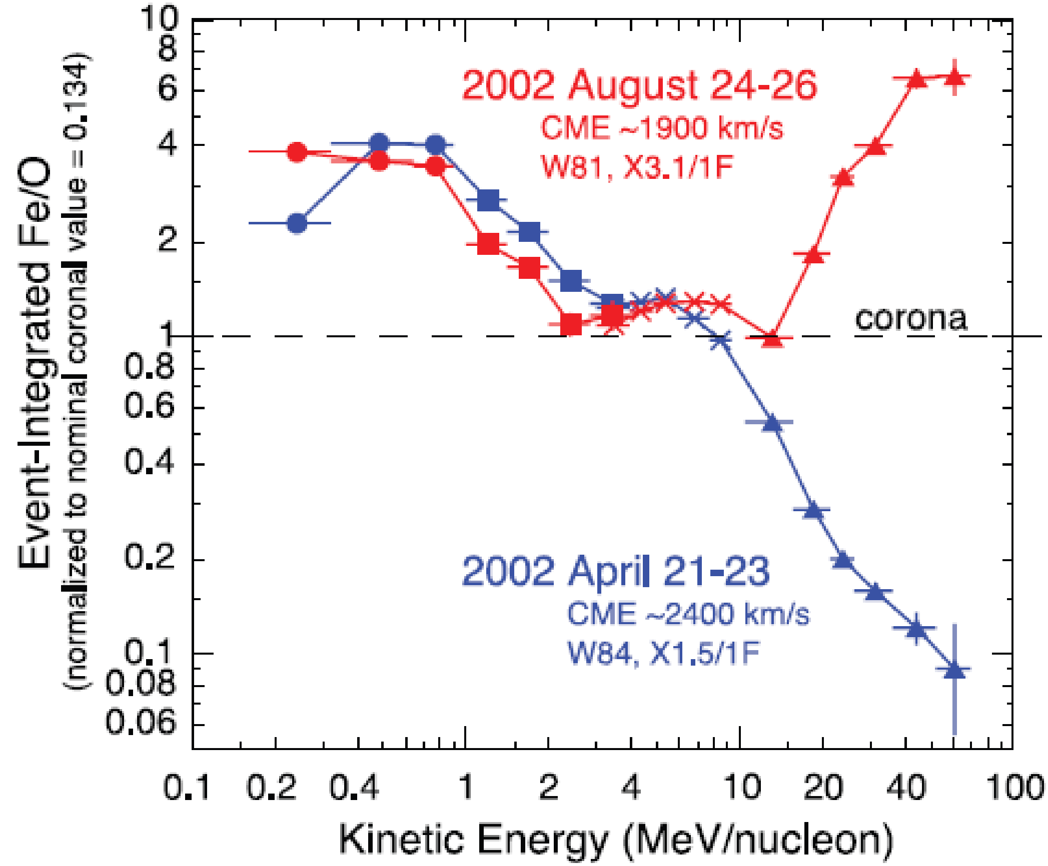
CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

What contributions do flare and shock-accelerated particles make to large solar particle events?

Enhanced Fe/O ratios are most often seen at energies >~ 10 MeV/nuc

What is the role of CME-driven shock geometry and (compound) seed population?

What is the contribution of concomitant flare-accelerated particles?



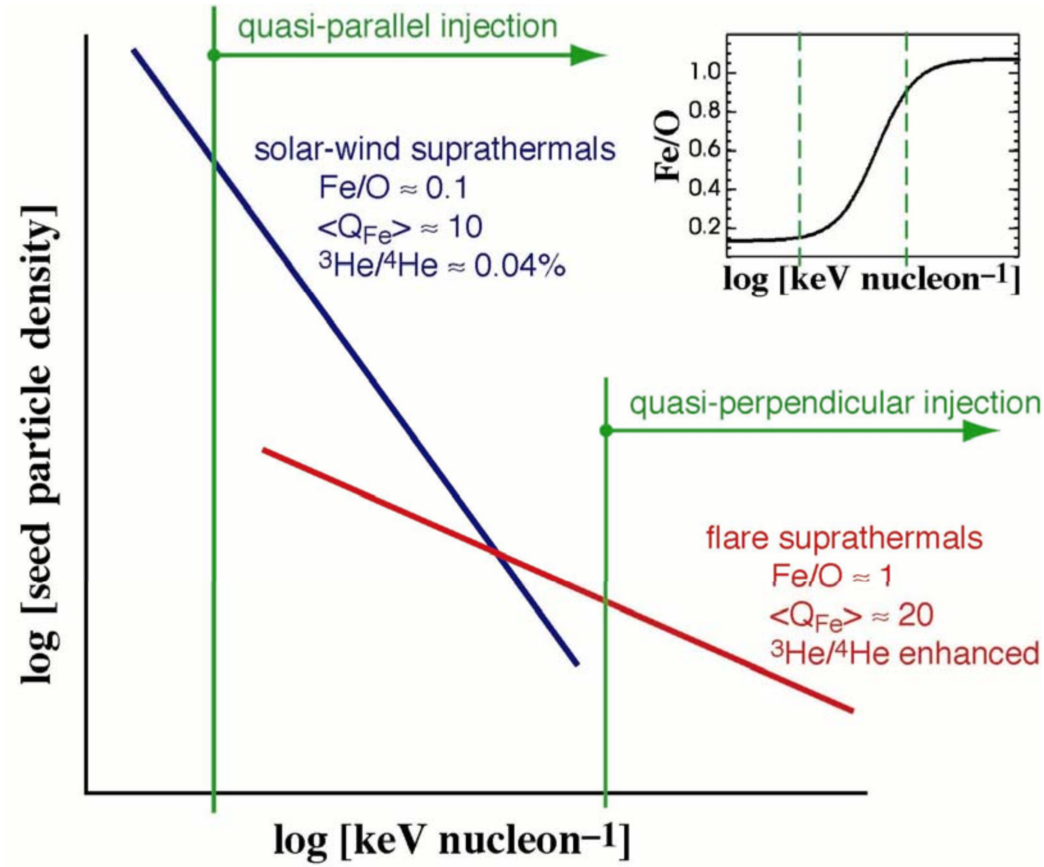
Tylka et al., 2006

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

2-component seed population:

- Solar wind suprathermals
- Flare suprathermals

Flare suprathermals are more efficiently accelerated at quasi-perpendicular shocks close to the Sun => attain highest energies



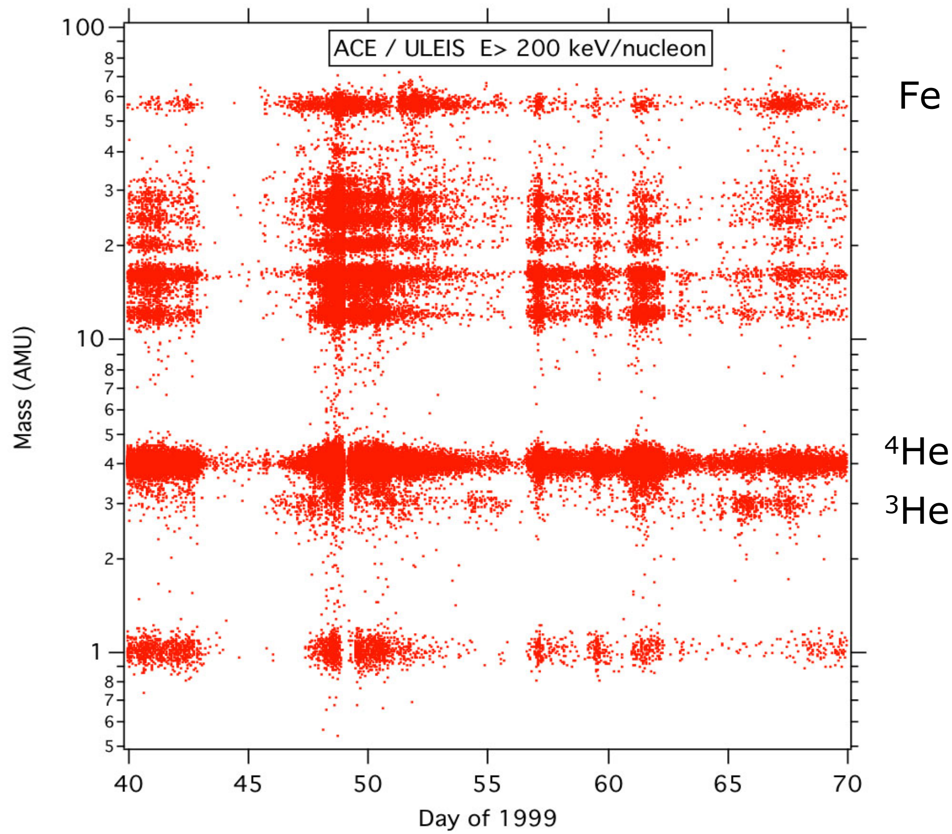
Tylka et al., 2005

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

Do Fe-rich SEP events occur because remnant flare suprathermals are more easily accelerated?

^{3}He and Fe are usually present in the interplanetary medium as a result of small impulsive events

However …



(Mason et al. 1999)

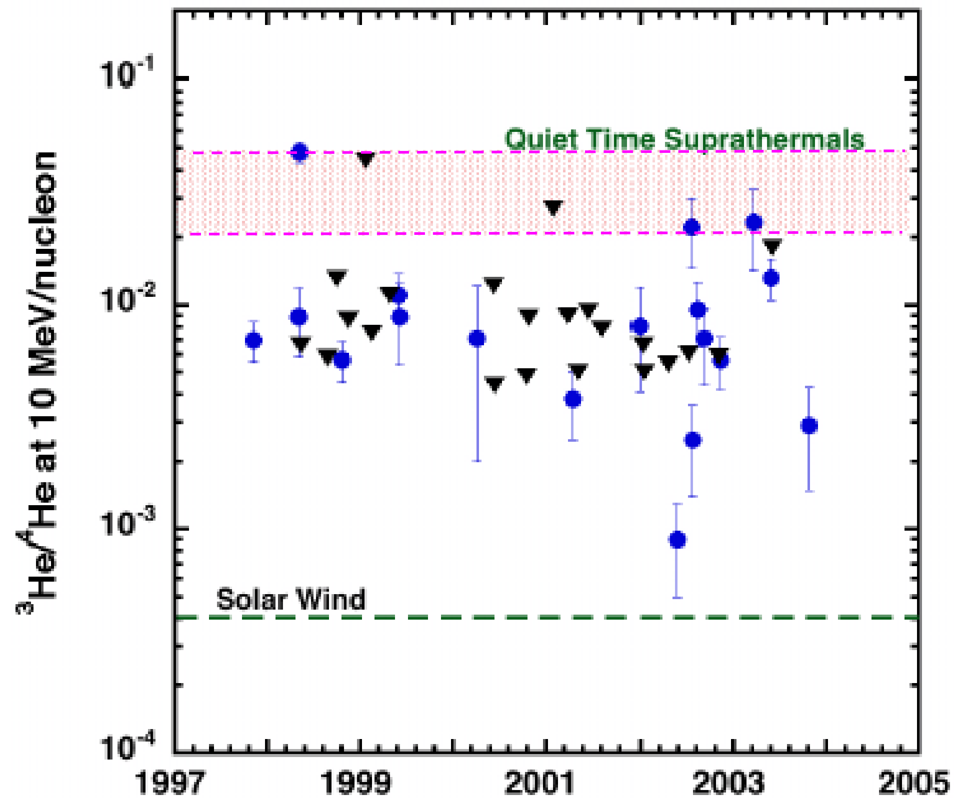
CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

Do Fe-rich SEP events occur because remnant flare suprathermals are more easily accelerated?

Only a small fraction of events at ~10 MeV/n have suprathermal-like $^3He/^4He$ enrichments (2-5%)

⇒Majority of 10 MeV/n He **not** remnant flare suprathermals

⇒Additional seed population needed (suprathermal tails?)

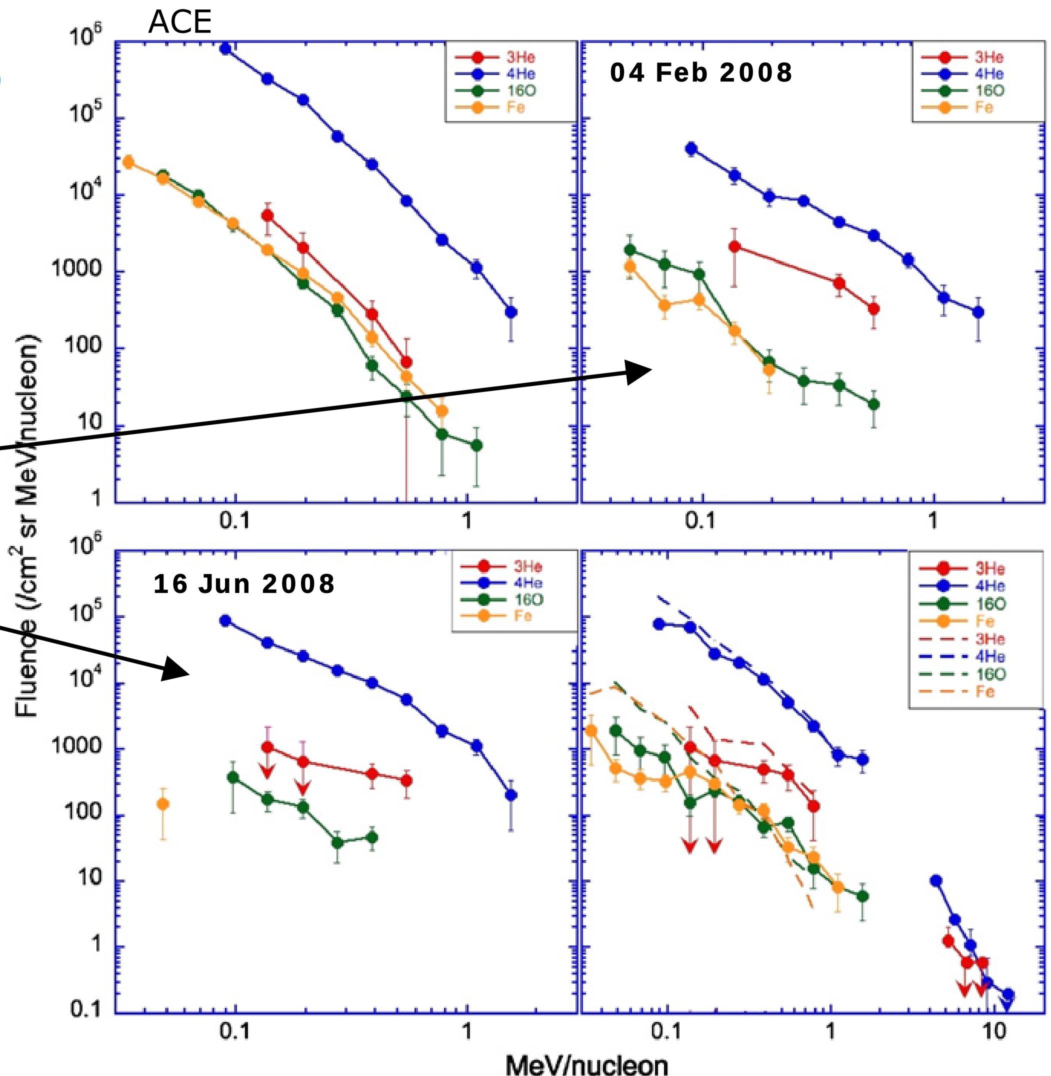


(Mewaldt et al. 2007)

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

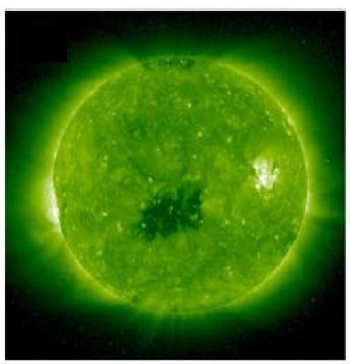
What processes are responsible for ^{3}He-rich events at solar minimum?

Mason et al., 2009



^{3}He enhancements (^{3}He/^{4}He >4%) observed in absence of X-ray signatures, type III, electrons

Association with W-hemisphere active region seems necessary condition

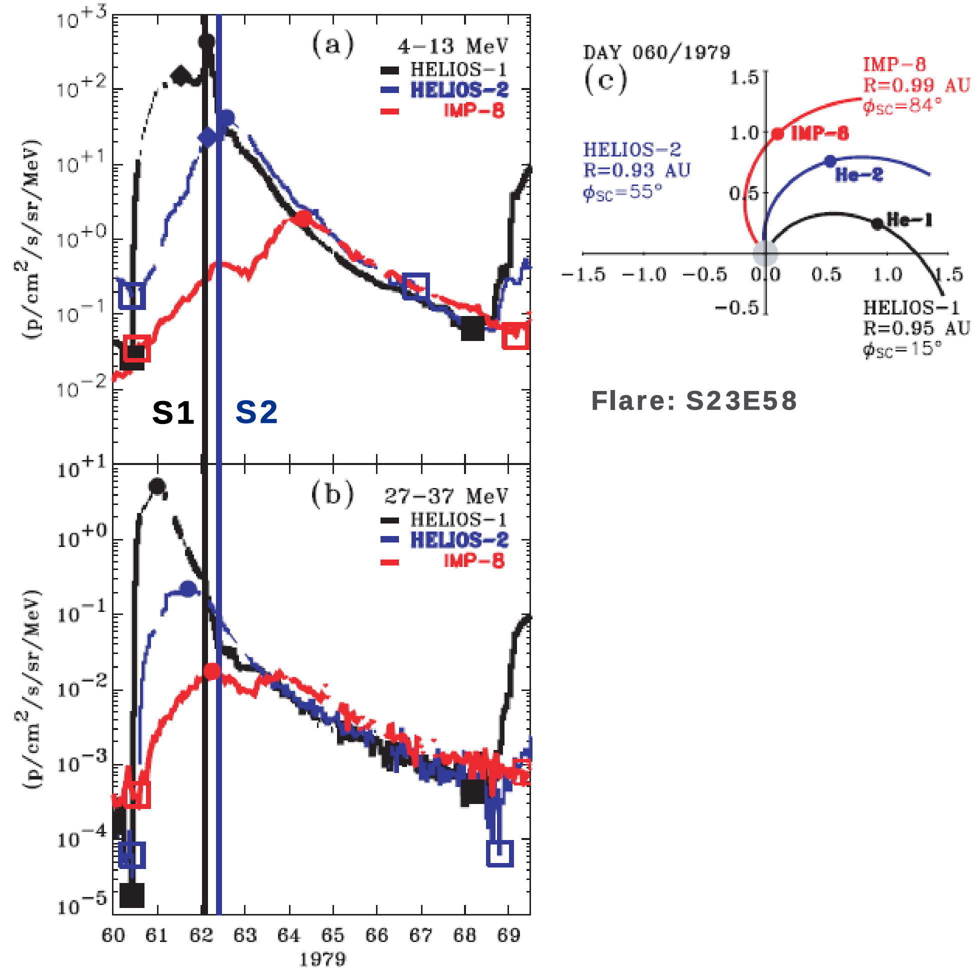


CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

Spatial dependence of peak flux and fluence: radius vs. longitude

– On average, azimuthal separation between observer's magnetic footpoint and flare site is more important than radial distance

– "Reservoir effect" often seen in the decaying phase of events: widely separated observers measure ~equal intensities (also out of ecliptic)



Flare: S23E58

Lario et al., 2006

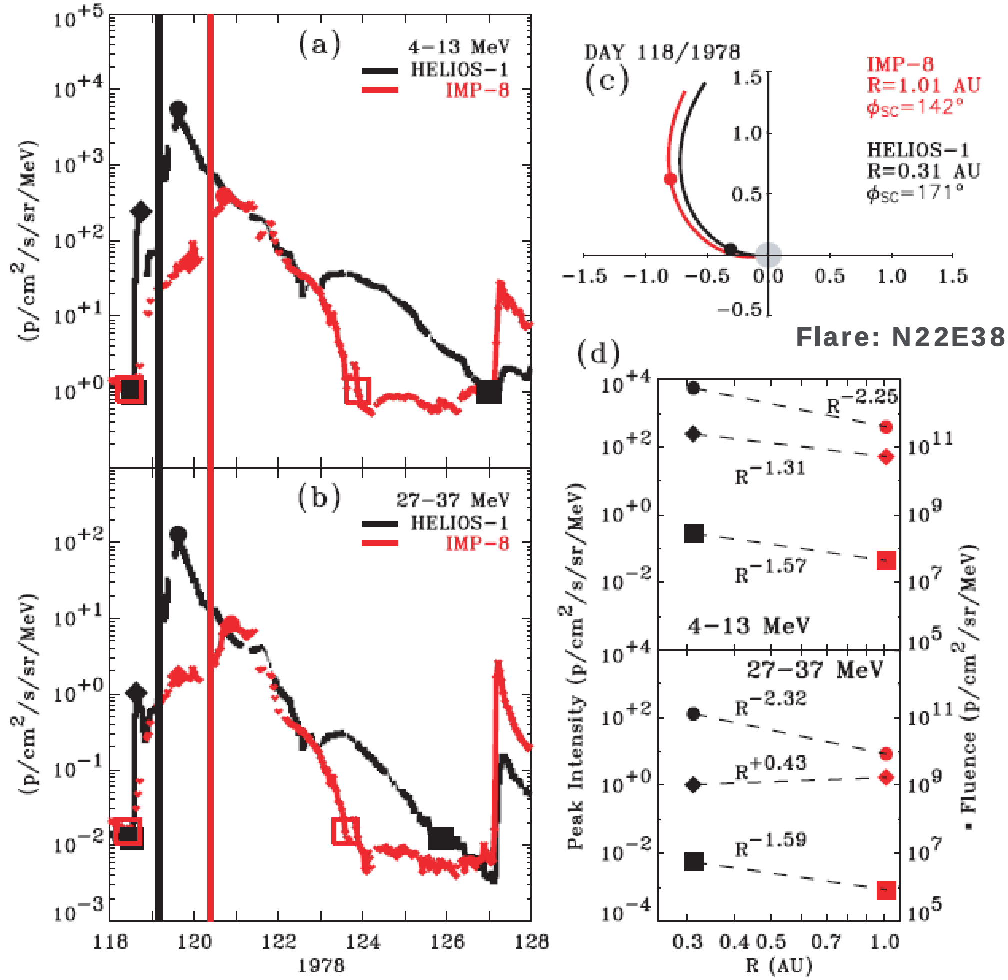
CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

Spatial dependence of peak flux and fluence: radius vs. longitude

–Radial dependence of peak flux and fluence is generally weaker than predicted by diffusive transport models (Hamilton et al., 1990):

–peak flux ~ $R^{-3.3}$

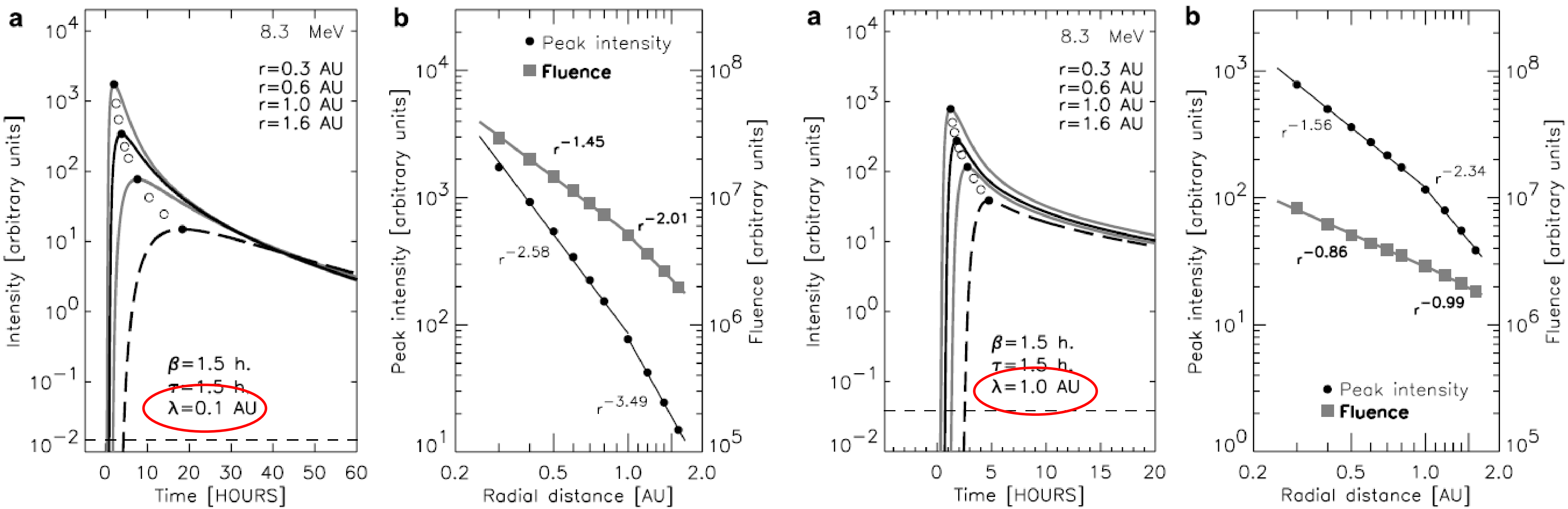
–fluence ~ $R^{-2.1}$



Lario et al., 2006

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

esa



Lario et al., 2007

Modeling:

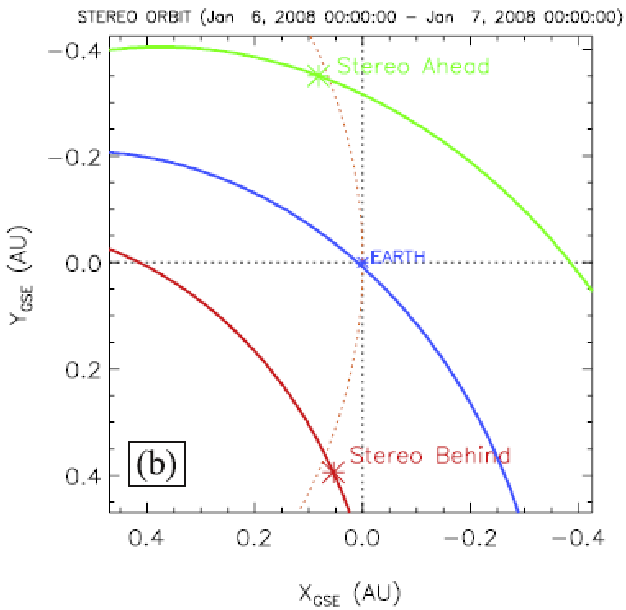
–Model based on focused-diffusion transport (e.g. Ruffolo, 1995) more appropriate than pure diffusion

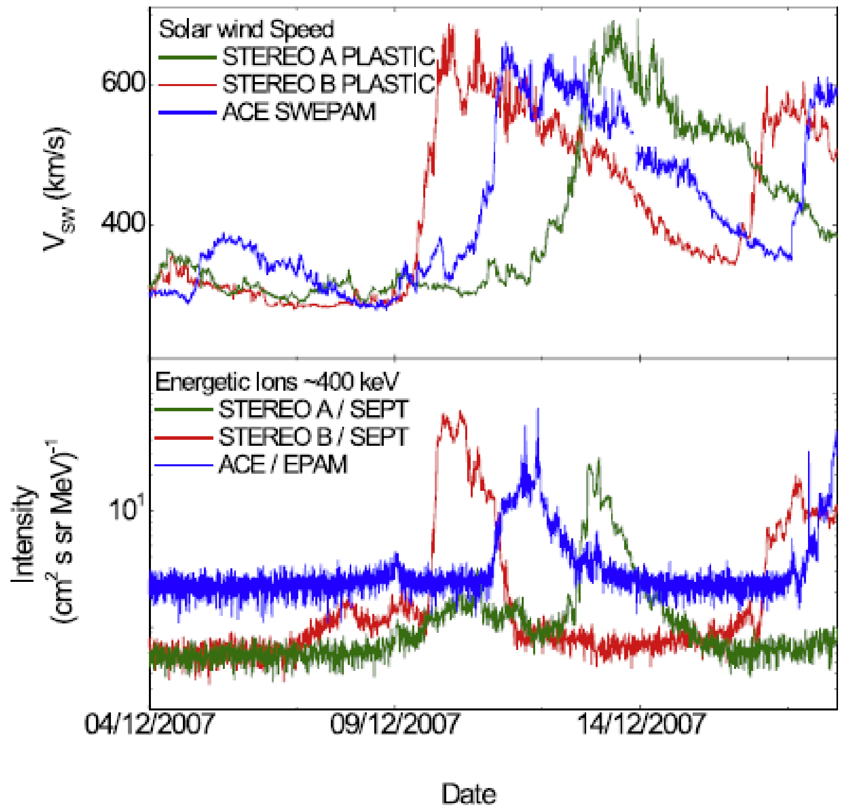
–Radial variation strongly dependent on particle mean free path λ and particle energy

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

CIR-related events (STEREO / ACE):

- Multi-S/C studies of CIR events at 1 AU
- Importance of spatial effects (radial and latitudinal separation) and temporal evolution of SW streams



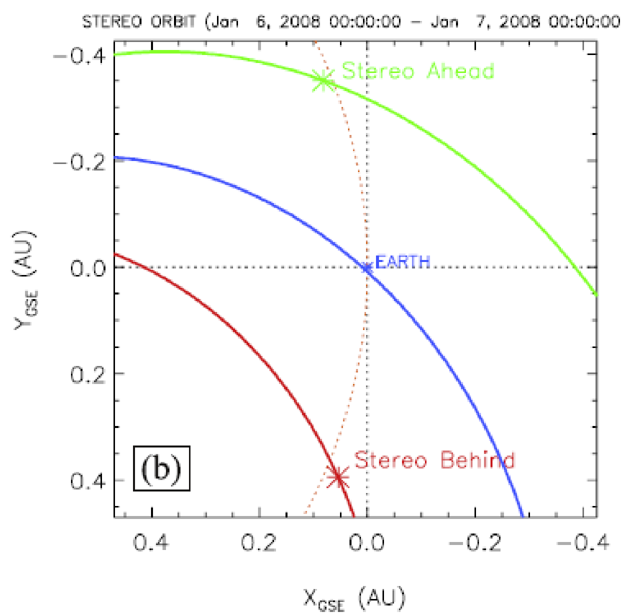


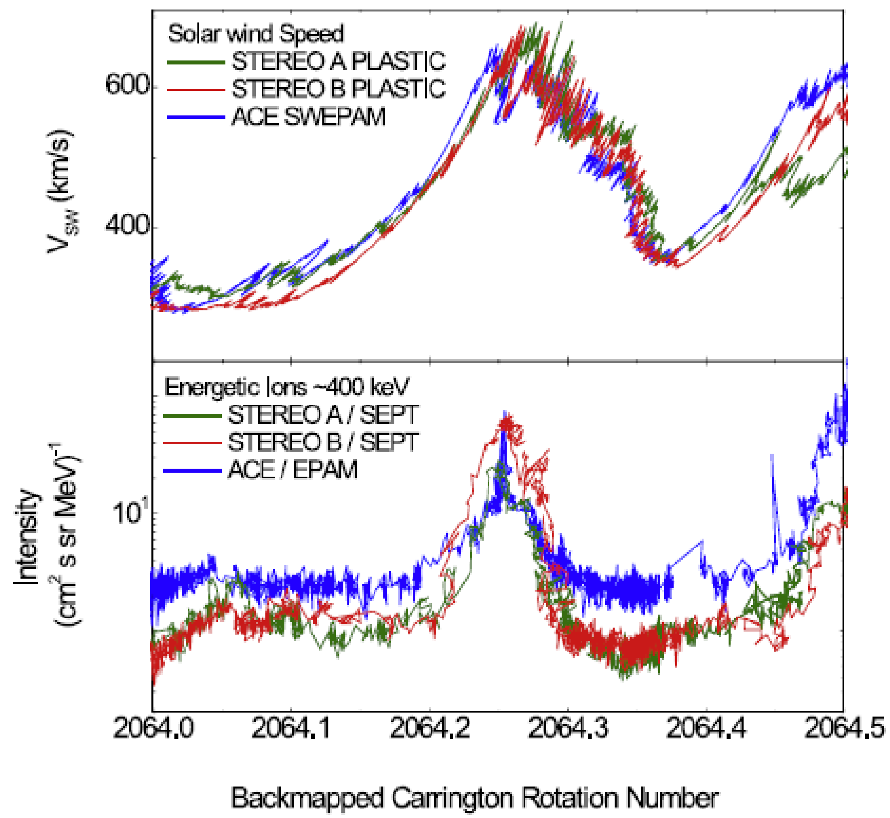
Gomez-Herrero et al., 2009

CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

CIR-related events (STEREO / ACE):

– Ballistic back-mapping useful tool



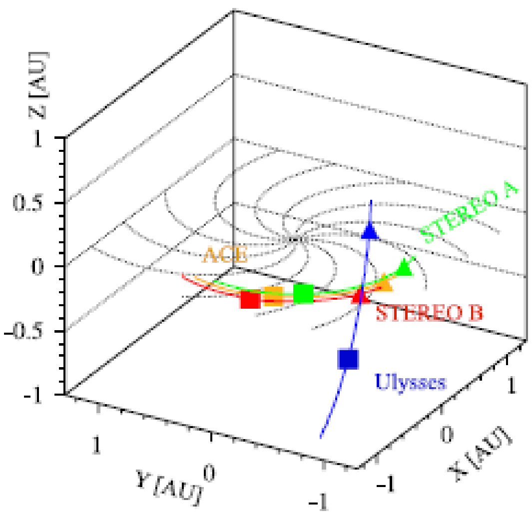


Gomez-Herrero et al., 2009

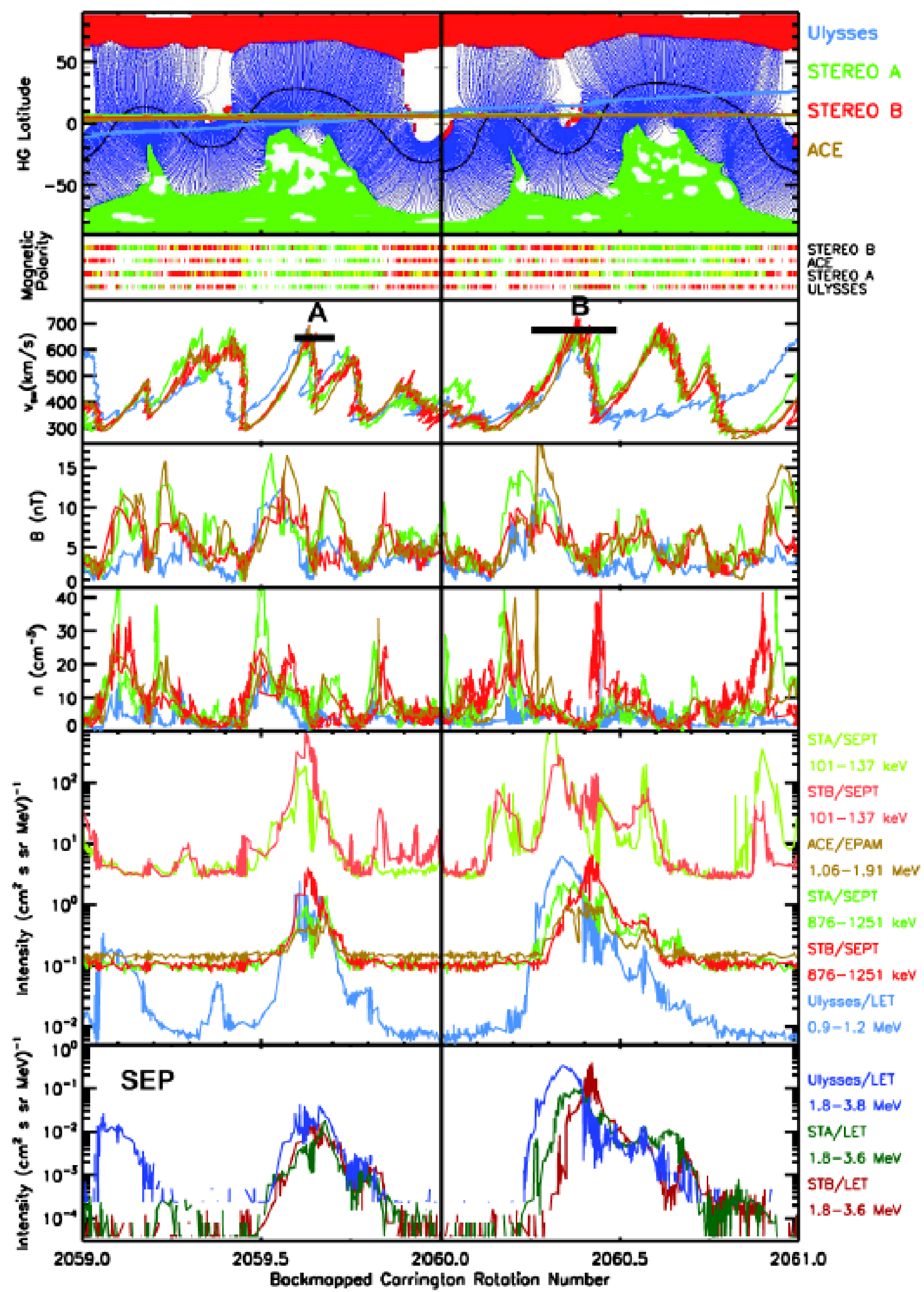
CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

CIR-related events (STEREO / ACE / ULYSSES):

- Radial gradient of CIR particles
- Ulysses at ~1.4 AU
- G_r ~ 230%/AU



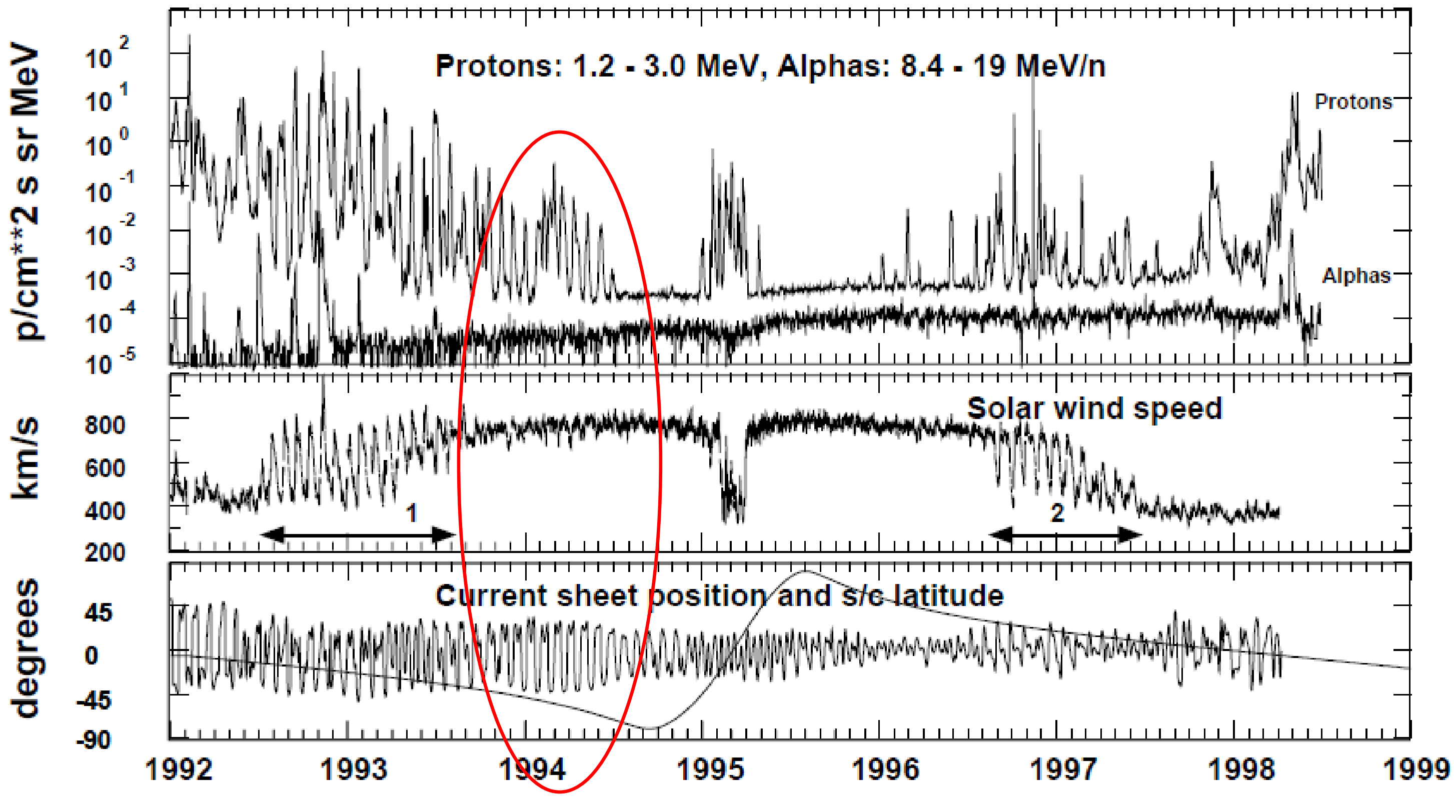
Dresing et al., 2009



CURRENT KNOWLEDGE (AND OPEN QUESTIONS)

Latitudinal transport (Ulysses):

- CIR-related increases observed at high latitudes in the fast solar wind
- Cross-field diffusion?
- High-latitude field lines connecting to interaction regions at low latitudes ("Fisk field")?
- Local acceleration at SW velocity gradients?



Sanderson et al., 1999

Q: What is needed to make progress?

A1: Observations <u>nearer the Sun</u>

– Combined remote-sensing and in-situ measurements
– Remote-sensing:
  – Imaging (White-light, X-rays, EUV, …) *and* (EUV) spectroscopy
– In-situ:
  – Conditions in the primary acceleration region(s)
  – Ion composition measurements (elemental, isotopic, charge-state) of seed populations and accelerated particles

A2: “Cradle-to-grave” modeling

Energetic particle observations in the inner heliosphere

Past, **Present and Future**

CURRENT & FUTURE MISSIONS < 1 AU

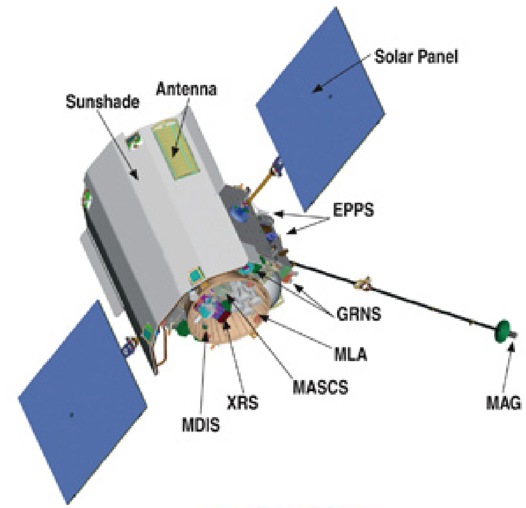
Messenger

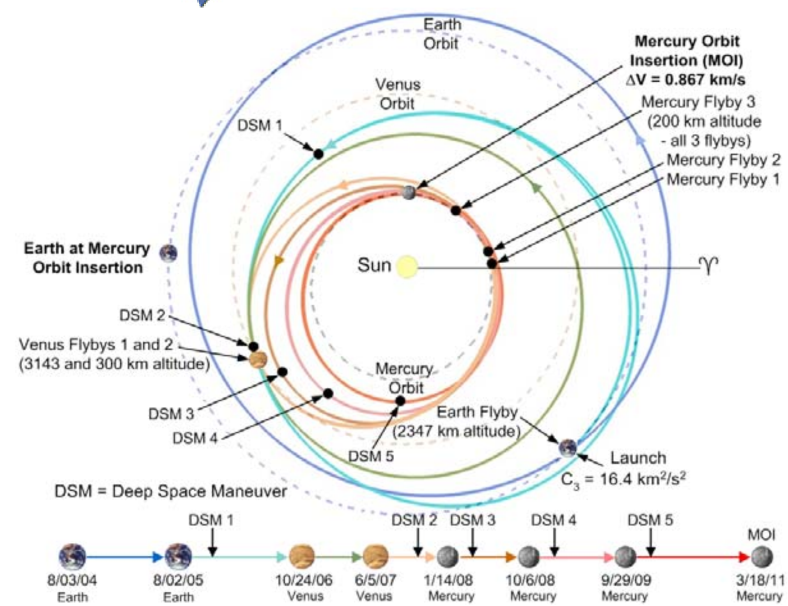
–Launch date: 2004-08-03

–Mercury fly-bys:

- 2008-01-14
- 2008-10-06
- 2009-09-29

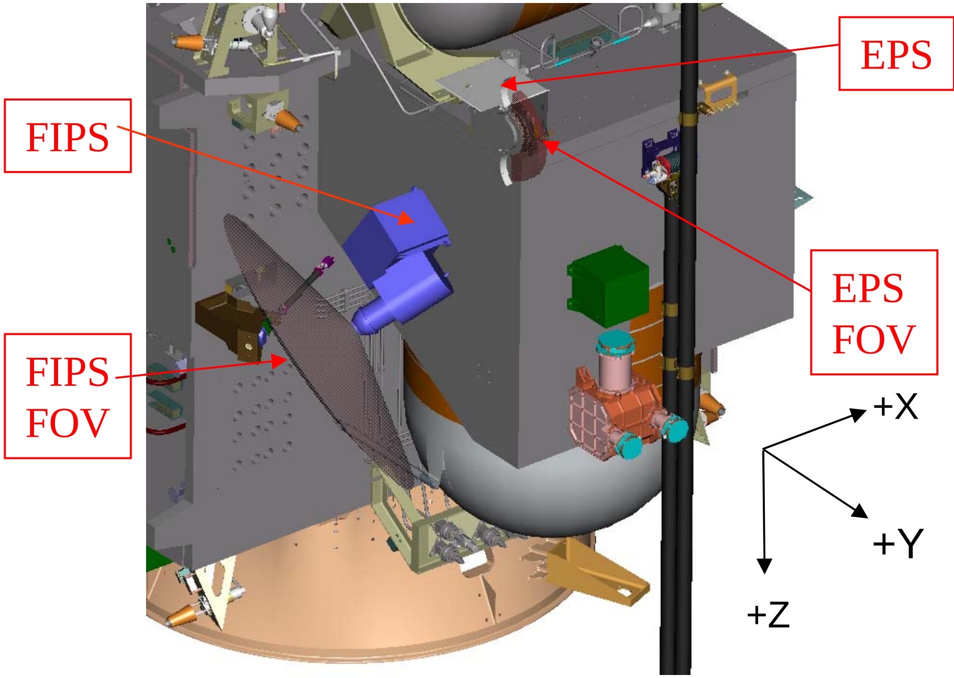
–Exploring the inner heliosphere (0.3 - 0.7 AU) from now to 2012





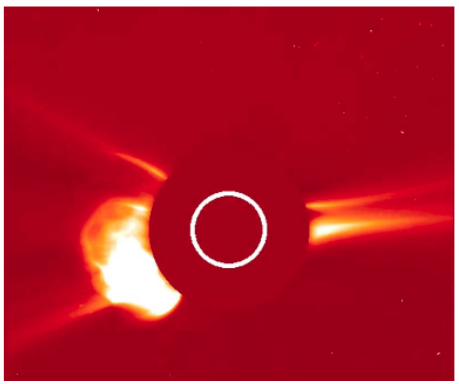
Messenger

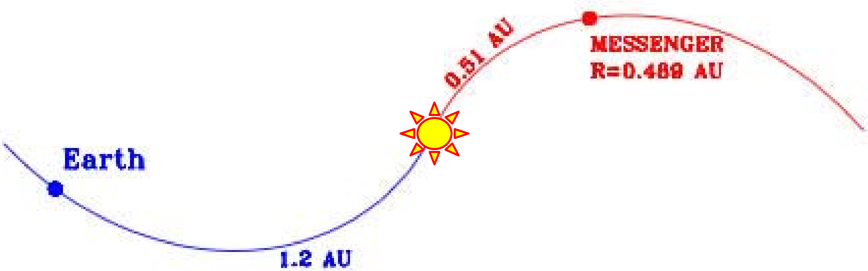
- Launch date: 2004-08-03
- Mercury fly-bys:
  - 2008-01-14
  - 2008-10-06
  - 2009-09-29
- Exploring the inner heliosphere (0.3 - 0.7 AU) from now to 2012
- Energetic Particle Spectrometer (EPS)
  - ions: 30 keV to 2.7 MeV
  - Electrons: 30 keV to 1 MeV

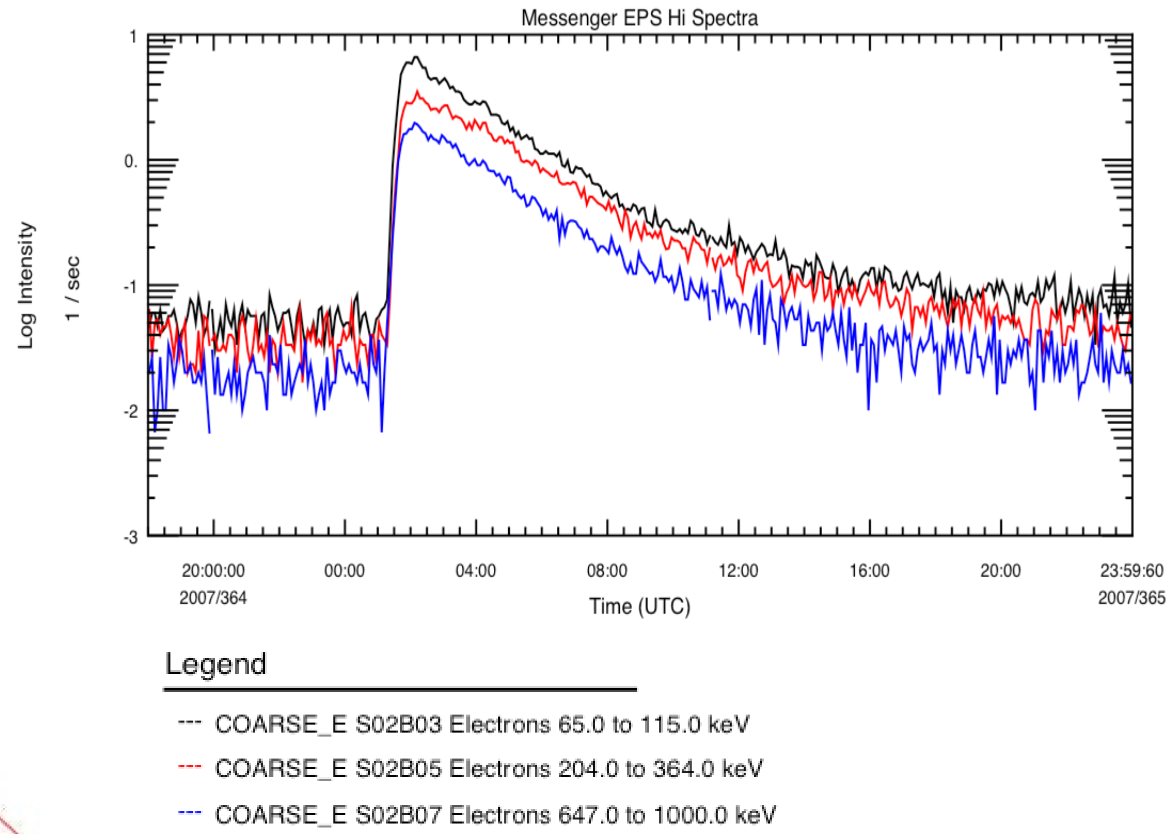


CURRENT & FUTURE MISSIONS < 1 AU

Messenger detected energetic electrons from the December 31 2007 E-limb event







Ho et al., 2008

CURRENT & FUTURE MISSIONS < 1 AU

BepiColombo

- Launch date: 2014
- Mercury arrival: 2020
- Mercury Planetary Orbiter (MPO):
  - Solar Intensity X-ray & particle Spectrometer (SIXS)
    - Primary objective: provide observations of solar X-ray and particle irradiation at Mercury's surface in support of Mercury Imaging X-ray Spectrometer (MIXS)
    - Secondary objective: monitoring of SEP fluxes and spectra
    - protons: 1 – 4.3 MeV; e^-: 0.1 – 0.3 MeV

CURRENT & FUTURE MISSIONS < 1 AU

Solar Obiter

–Launch date: Jan 2017

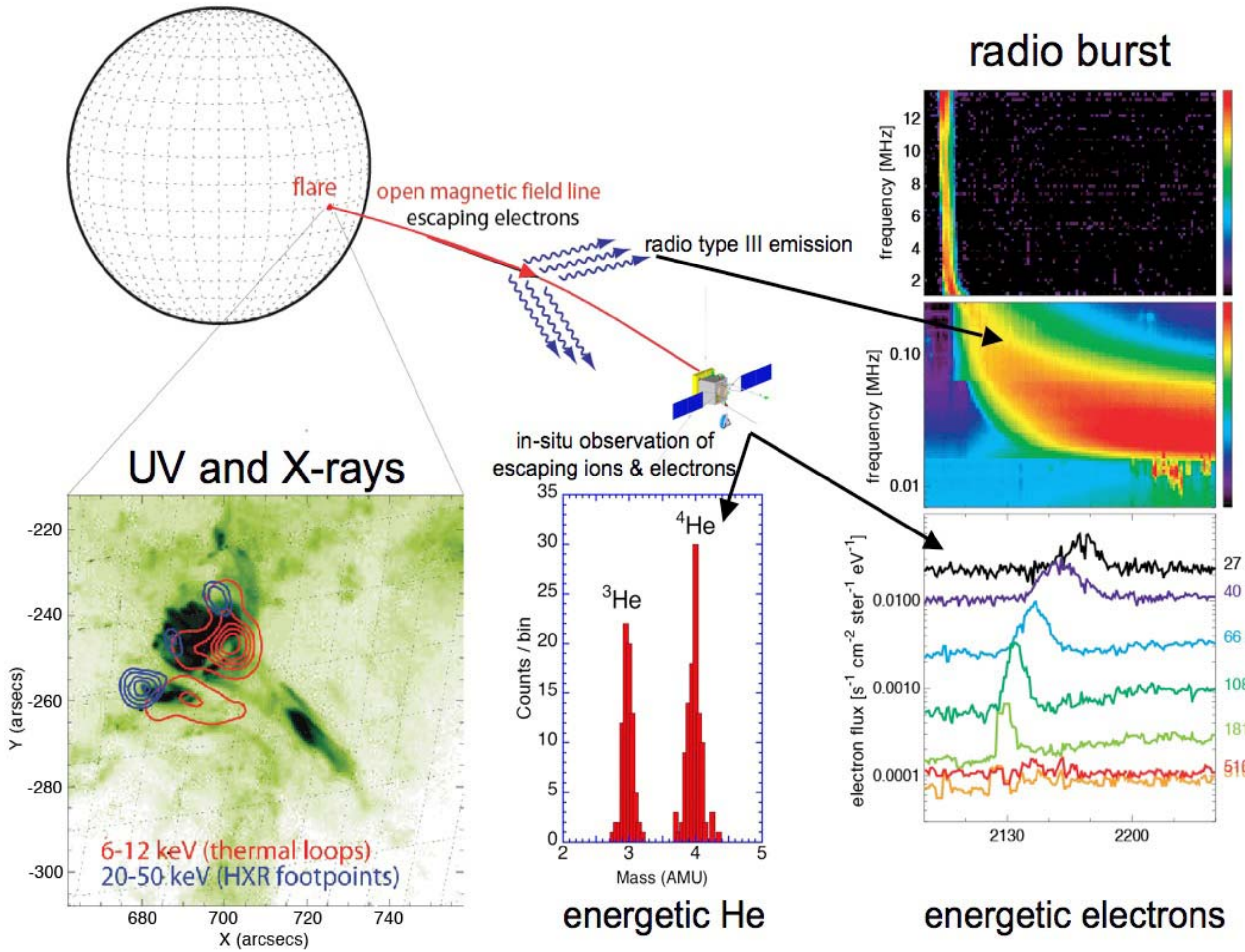
–Key objective: Explore how the Sun creates and controls the Heliosphere

–Science questions:

- How and where do the solar wind plasma and magnetic field originate in the corona?
- 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?

CURRENT & FUTURE MISSIONS < 1 AU

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



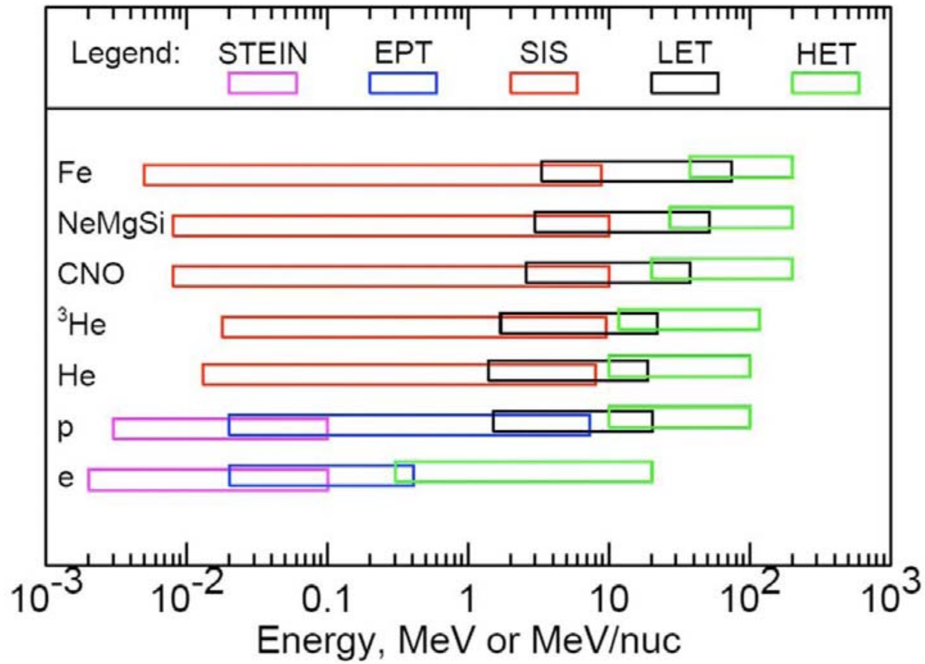
CURRENT & FUTURE MISSIONS < 1 AU

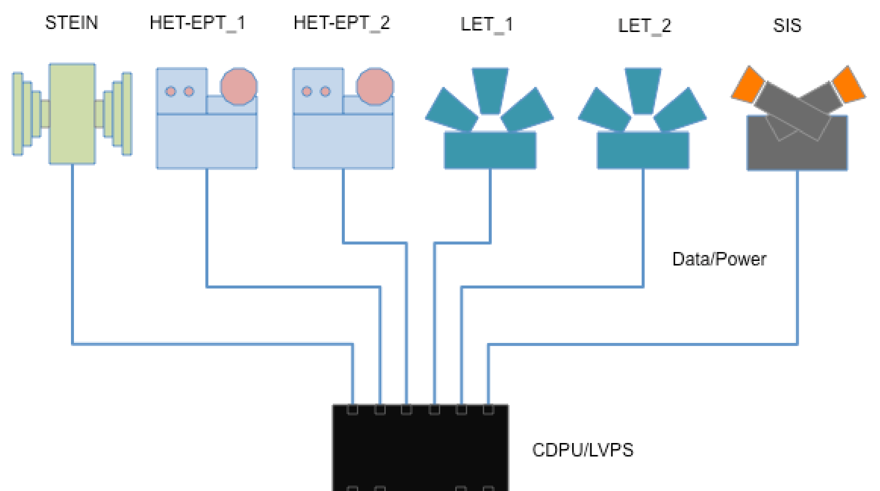
Solar Orbiter Energetic Particle Detector (EPD)

- PI: J. Rodriguez-Pacheco (Univ. Alcala)

Sensors:

- SupraThermal Electrons, Ions, & Neutrals (STEIN)
- Suprathermal Ion Spectrograph (SIS)
- Electron Proton Telescope (EPT)
- Low Energy Telescope (LET)
- High Energy Telescope (HET)

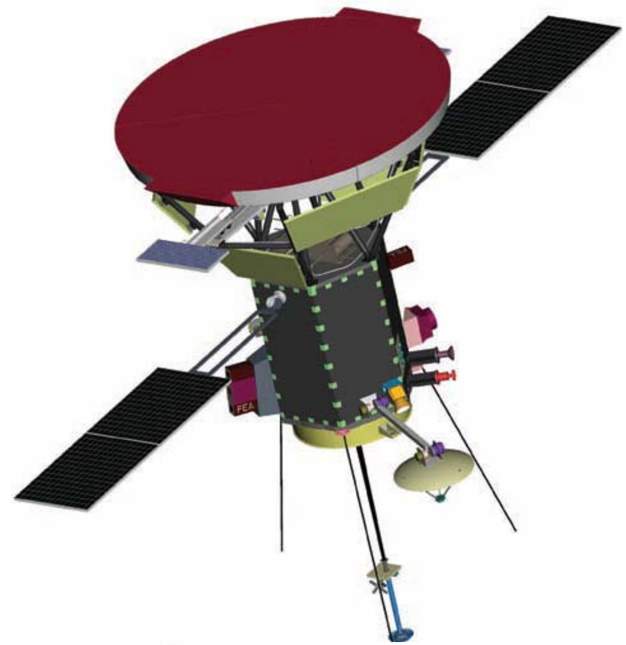


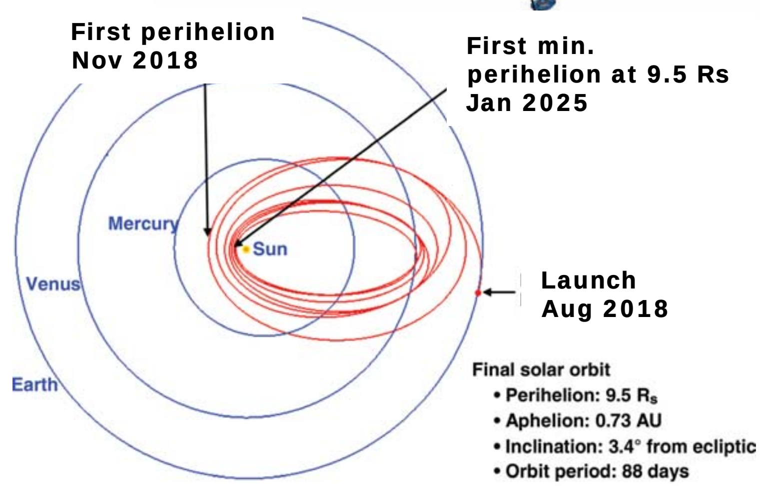


CURRENT & FUTURE MISSIONS < 1 AU

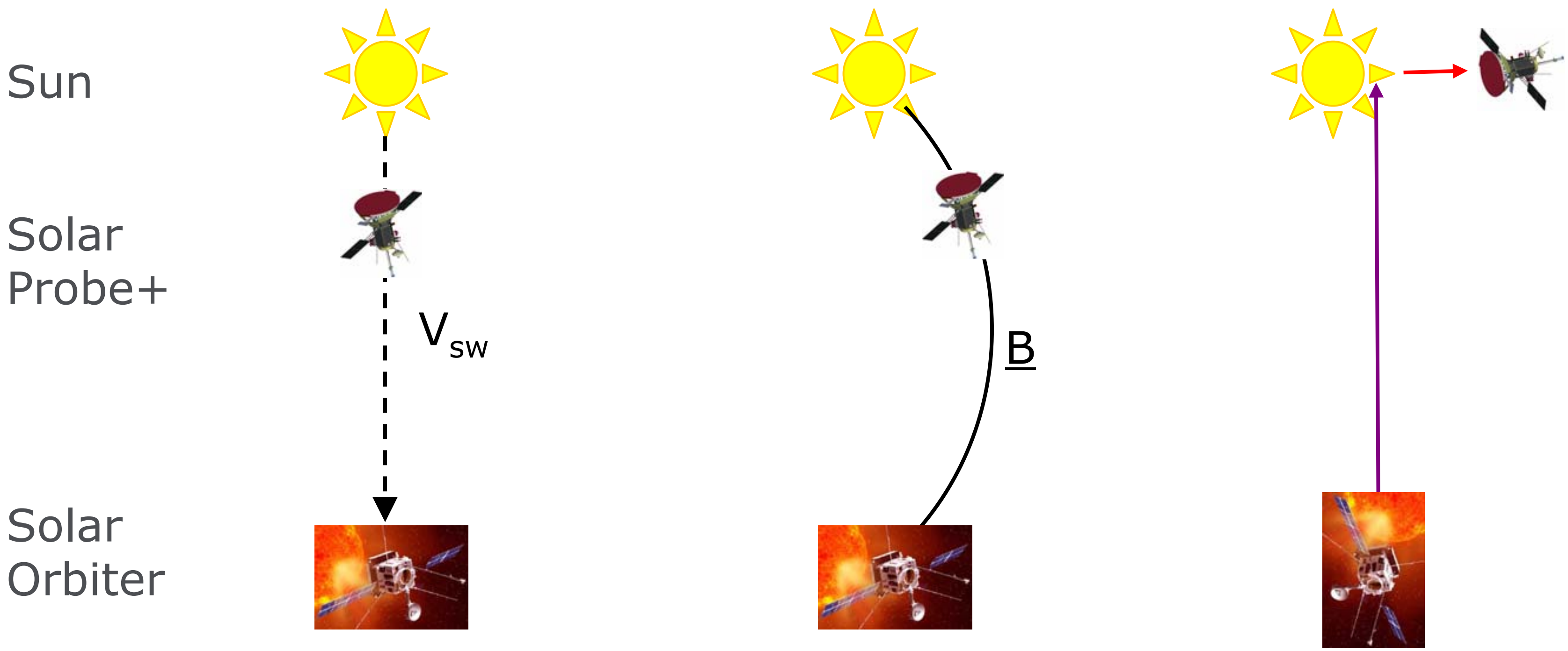
Solar Probe Plus

- Launch date: Aug 2018
- Closest approach to Sun: 9.5 Rs
- Key objectives:
  - Determine the structure and dynamics of the magnetic fields at the sources of both fast and slow solar wind
  - Trace the flow of energy that heats the corona and accelerates the solar wind
  - **Determine what mechanisms accelerate and transport energetic particles**
  - Explore dusty plasma phenomena near the Sun and its influence on the solar wind and energetic particle formation





Solar Orbiter / Solar Probe + joint science



Radial alignments:

SO and SPP observe the same SW plasma

IMF alignments:

SO and SPP connect to the same IMF footpoint

Quadratures:

SO remote-sensing and SPP in-situ @ ≥9.5 Rs

SUMMARY

1. Much has been learned about energetic particle populations in the heliosphere since the first in-situ observations ~50 years ago

2. Major questions still remain concerning sources, acceleration mechanisms and transport processes

3. New, near-Sun, observations from missions like Solar Orbiter, Solar Probe Plus and (hopefully) Inner Heliospheric Sentinels promise to bring major break-throughs

4. Stay tuned!

THANK YOU

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