Energetic Particles in the Heliosphere and their Impacts on Geospace

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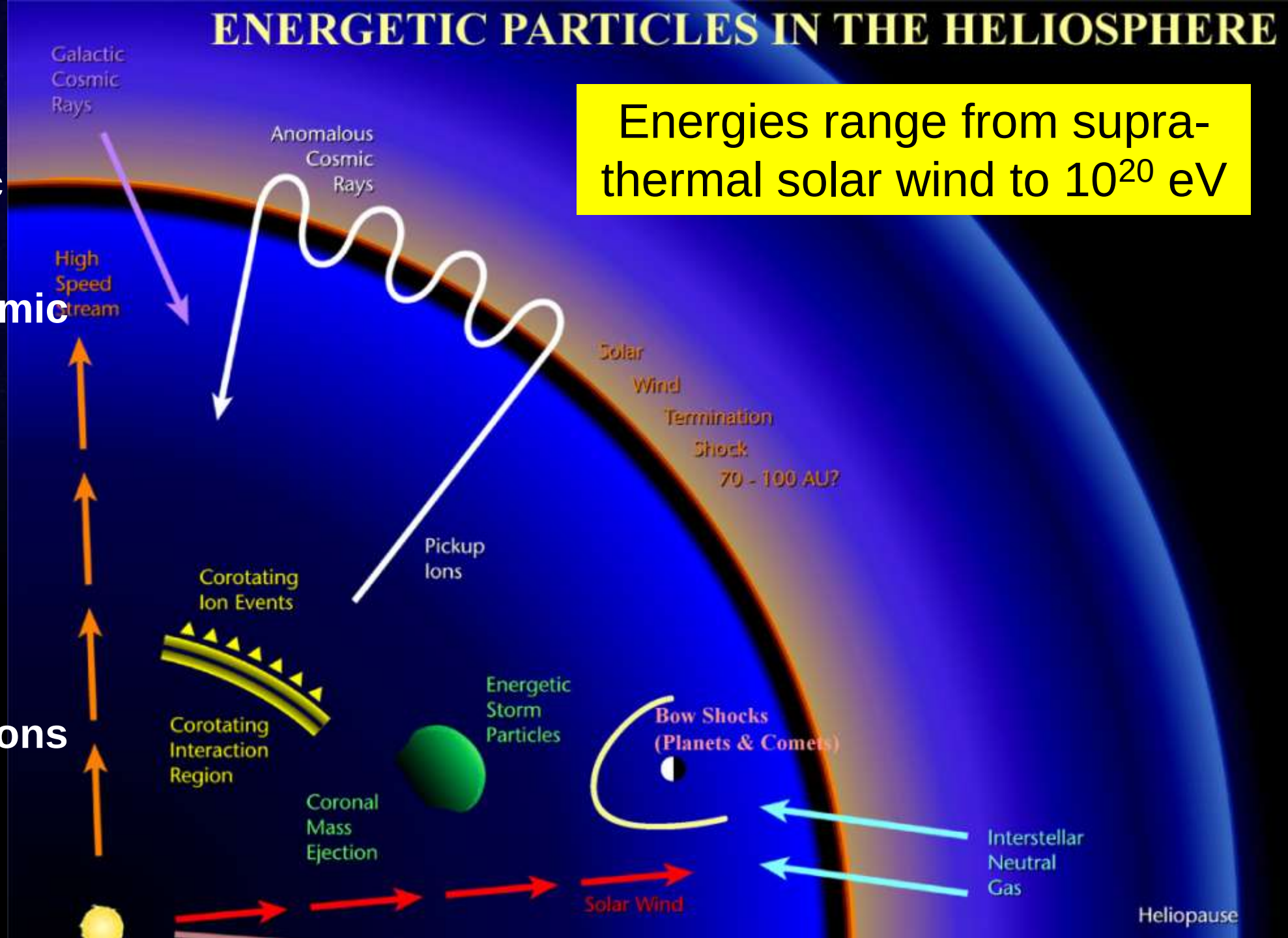
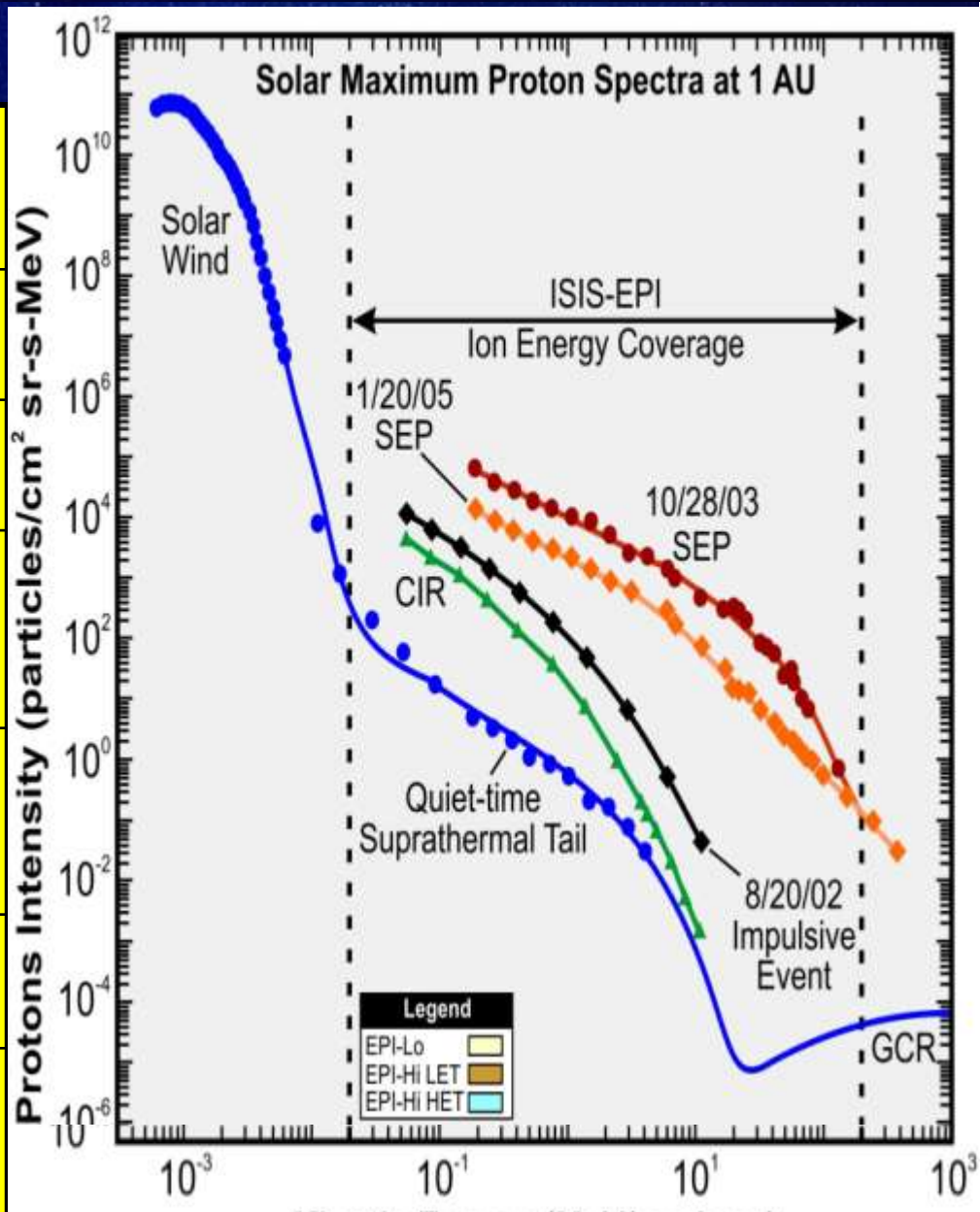
- **Galactic Cosmic Rays (GCRs)**
- **Anomalous Cosmic Rays (ACRs)**
- **Solar Energetic Particles (SEPs)**
- **Energetic Storm Particles (ESPs)**
- **Corotating Interaction Regions (CIRs)**
- **Planetary Bow shocks**



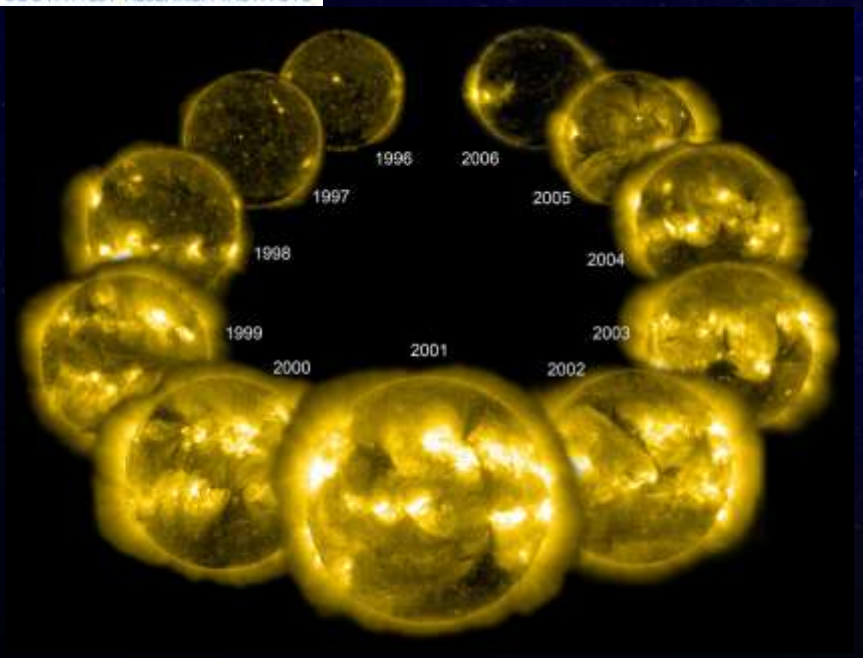
Energies range from supra-thermal solar wind to 10^{20} eV

Overview of Particle Populations

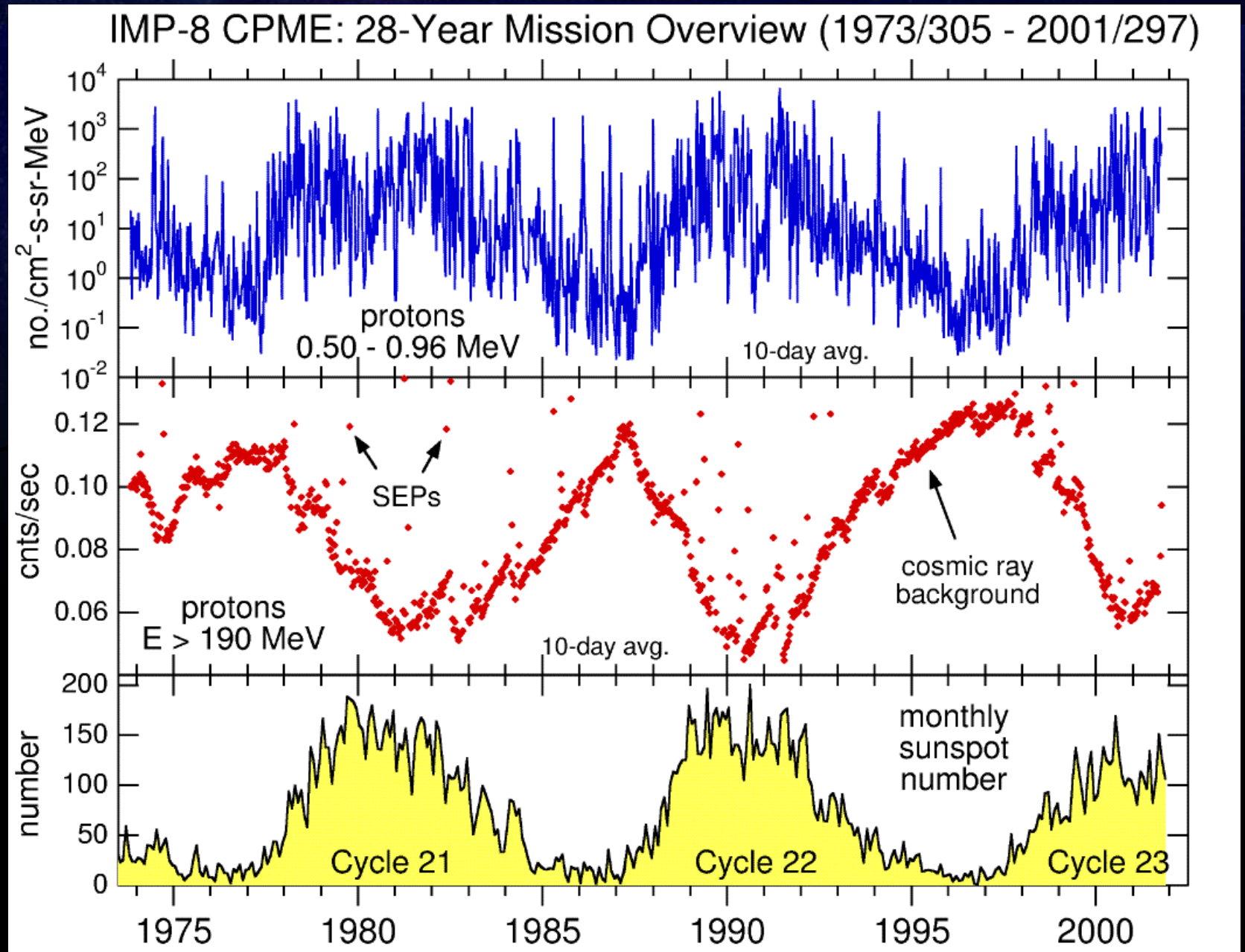
Particle Population	Temporal scales	Spatial scales	Energy range	Acceleration mechanisms
GCRs	continuous	global	GeV --->TeV	Diffusive shock
ACRs	continuous	Global	10-100 MeV	Diffusive shock, shock drift, or other?
CIRs	27 days	Large-scale	keV ---> 10 MeV	Diffusive shock, shock drift, stochastic
SEPs	δ	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



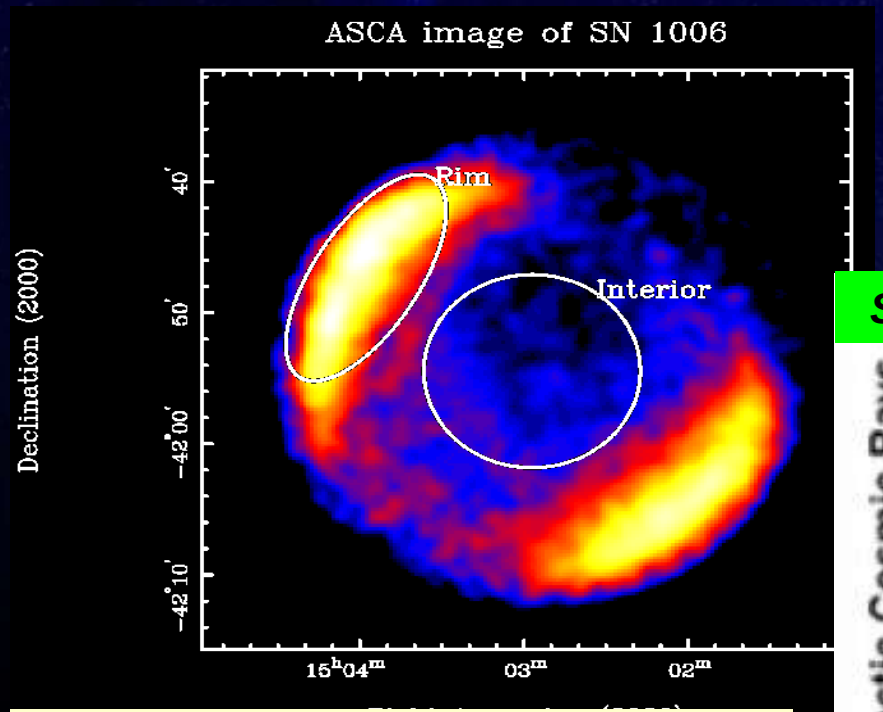
Solar cycle dependence



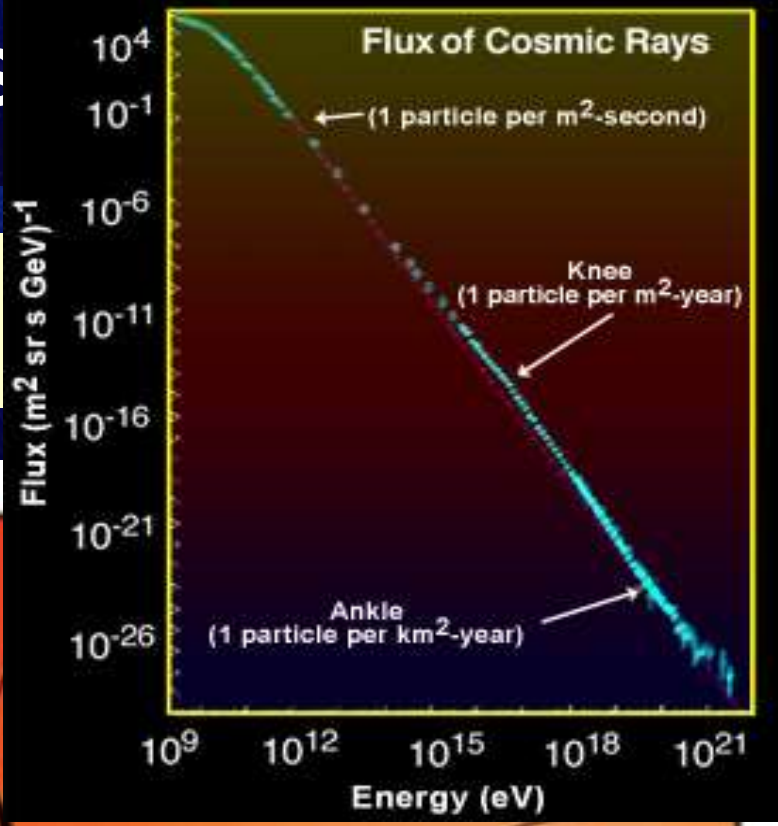
- GCRs/ACRs/CIRs have higher intensities during solar min. and reduced intensities during solar max
- SEPs are more frequent during solar maximum, but also occur during solar minimum



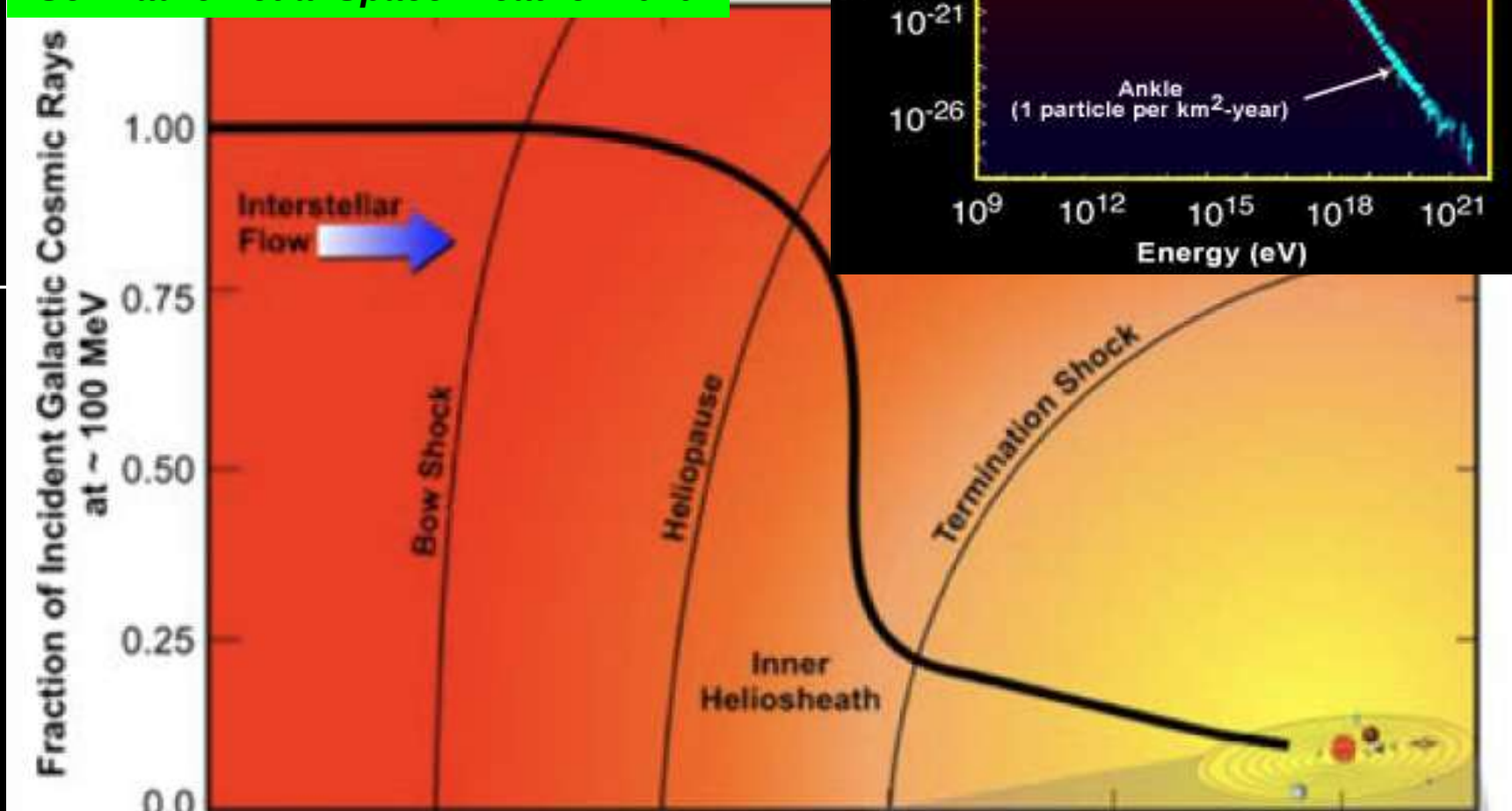
Galactic Cosmic Rays



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

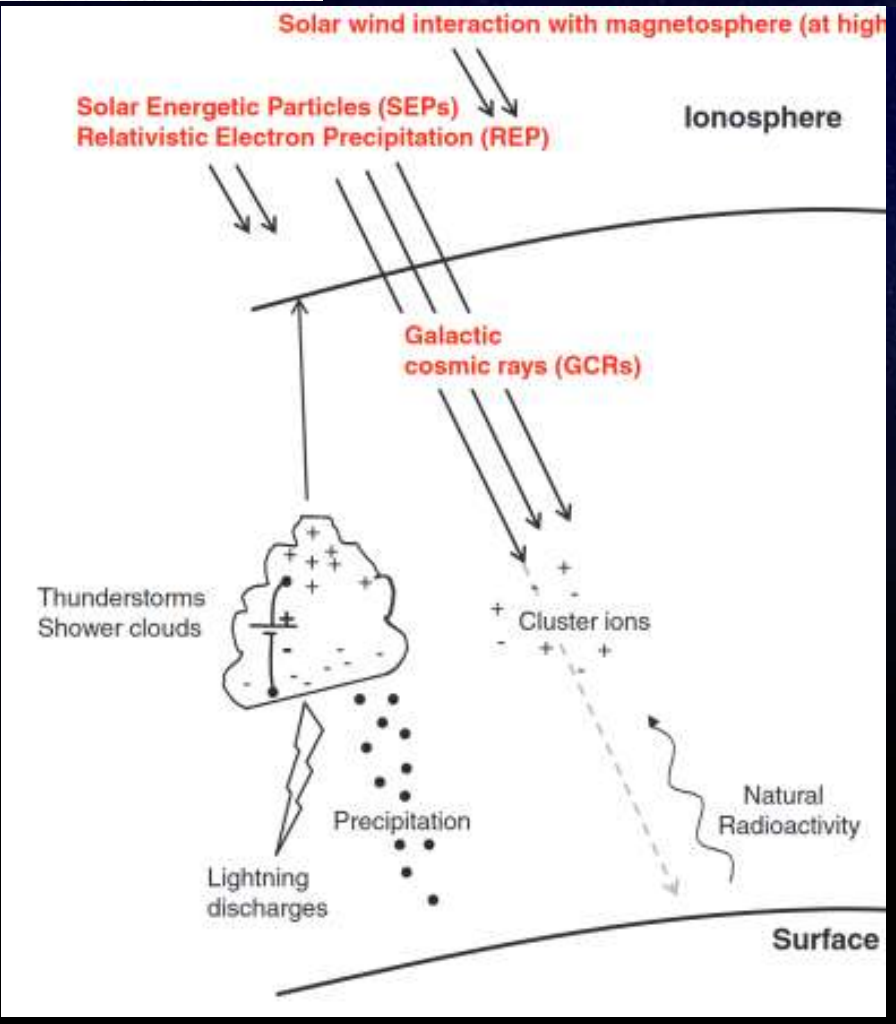


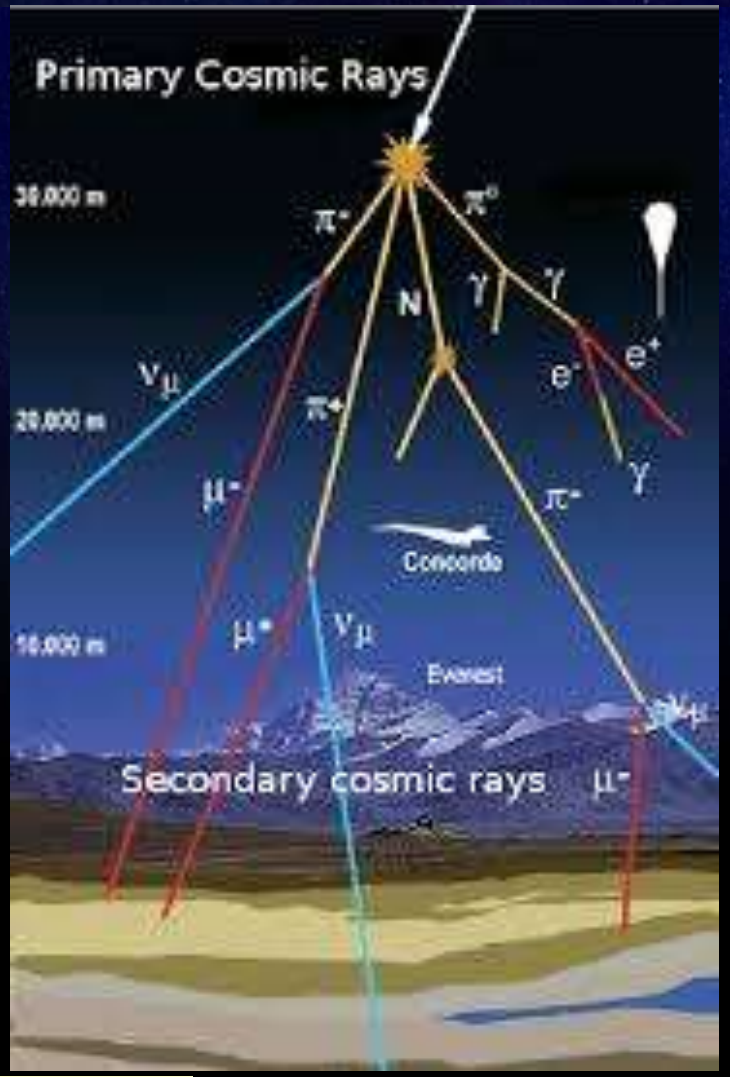
Schwadron et al Space Weather 2010

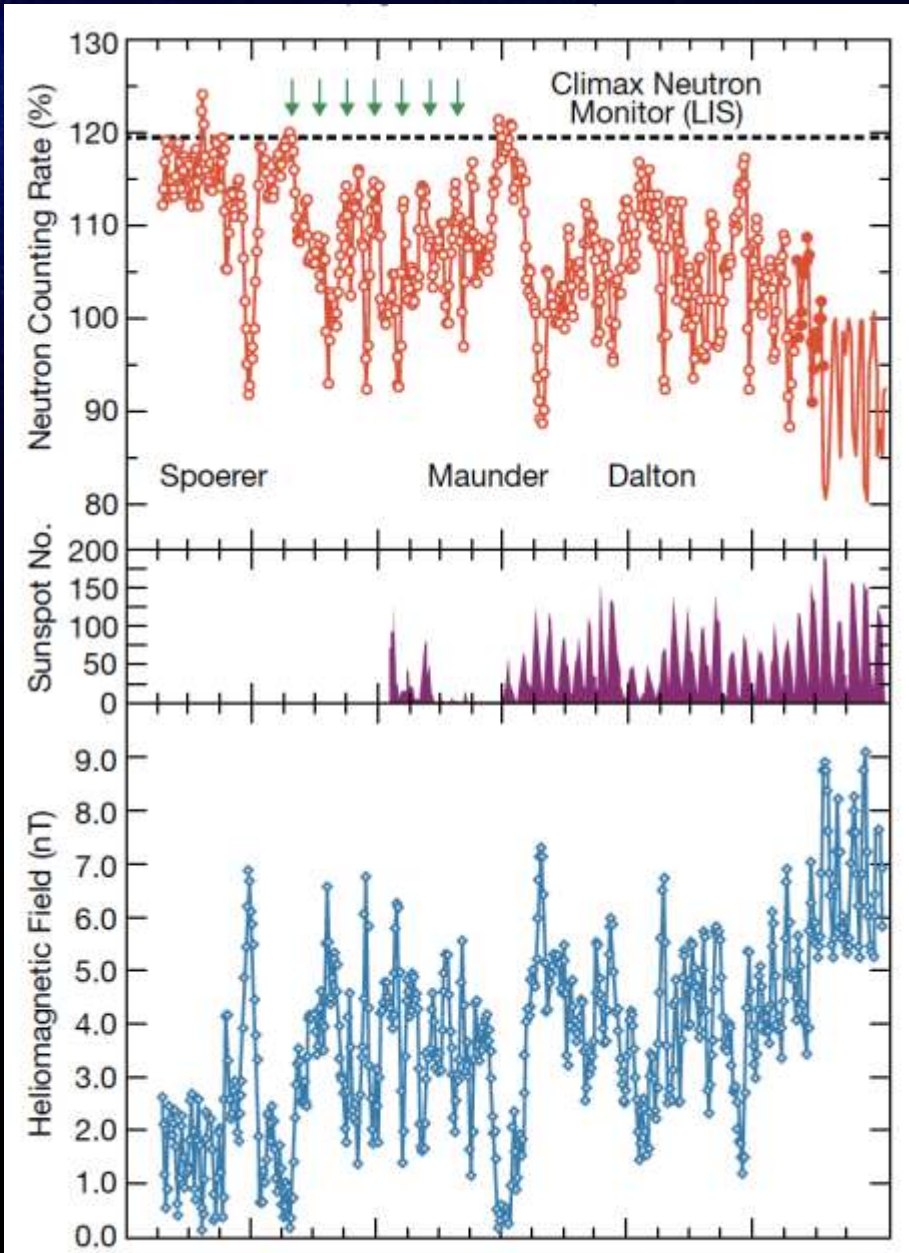


- Produced during supernovae explosions that create relativistic shocks
- GCRs are modulated (fluxes are reduced) in the heliosphere

GCR effects in Geospace

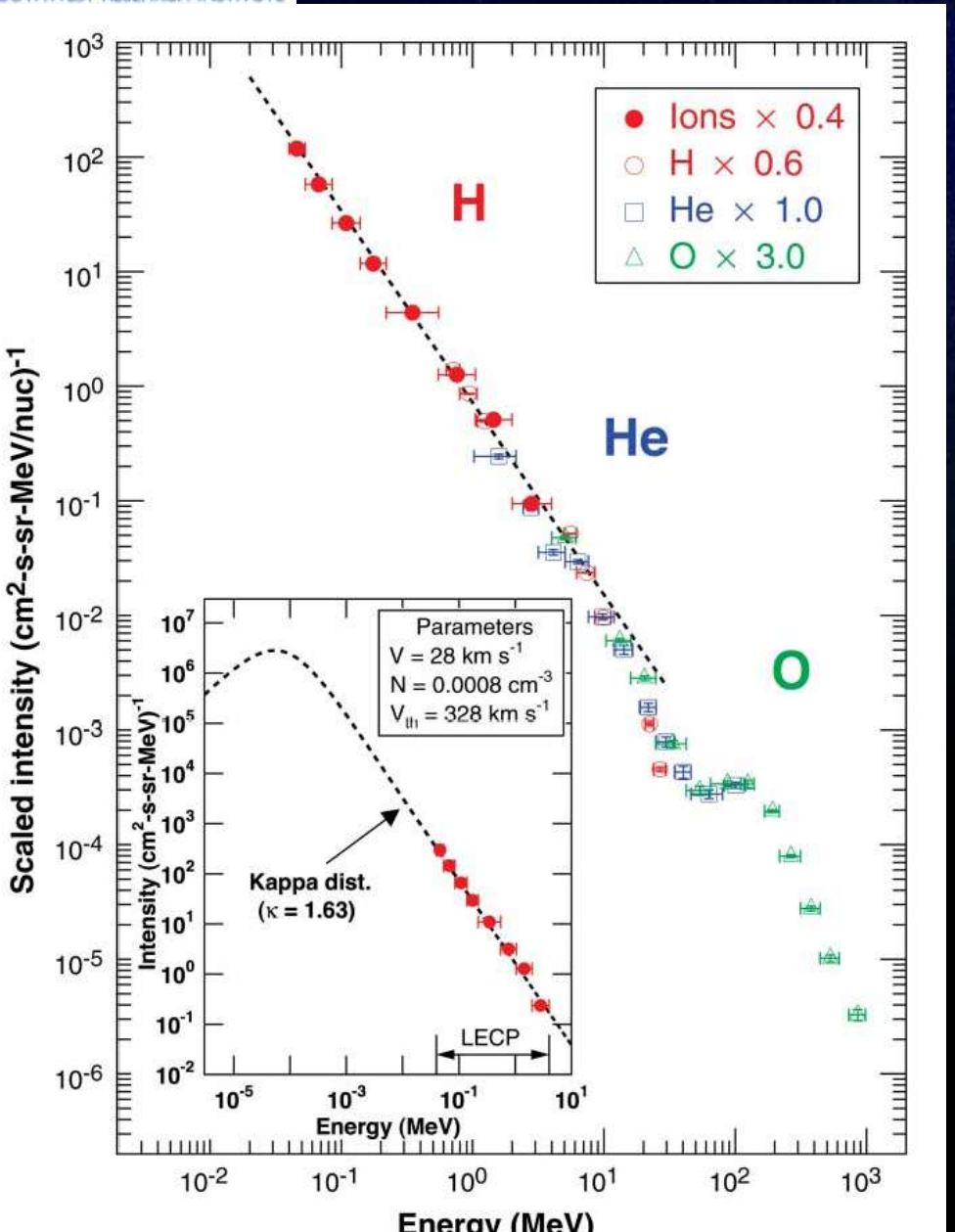


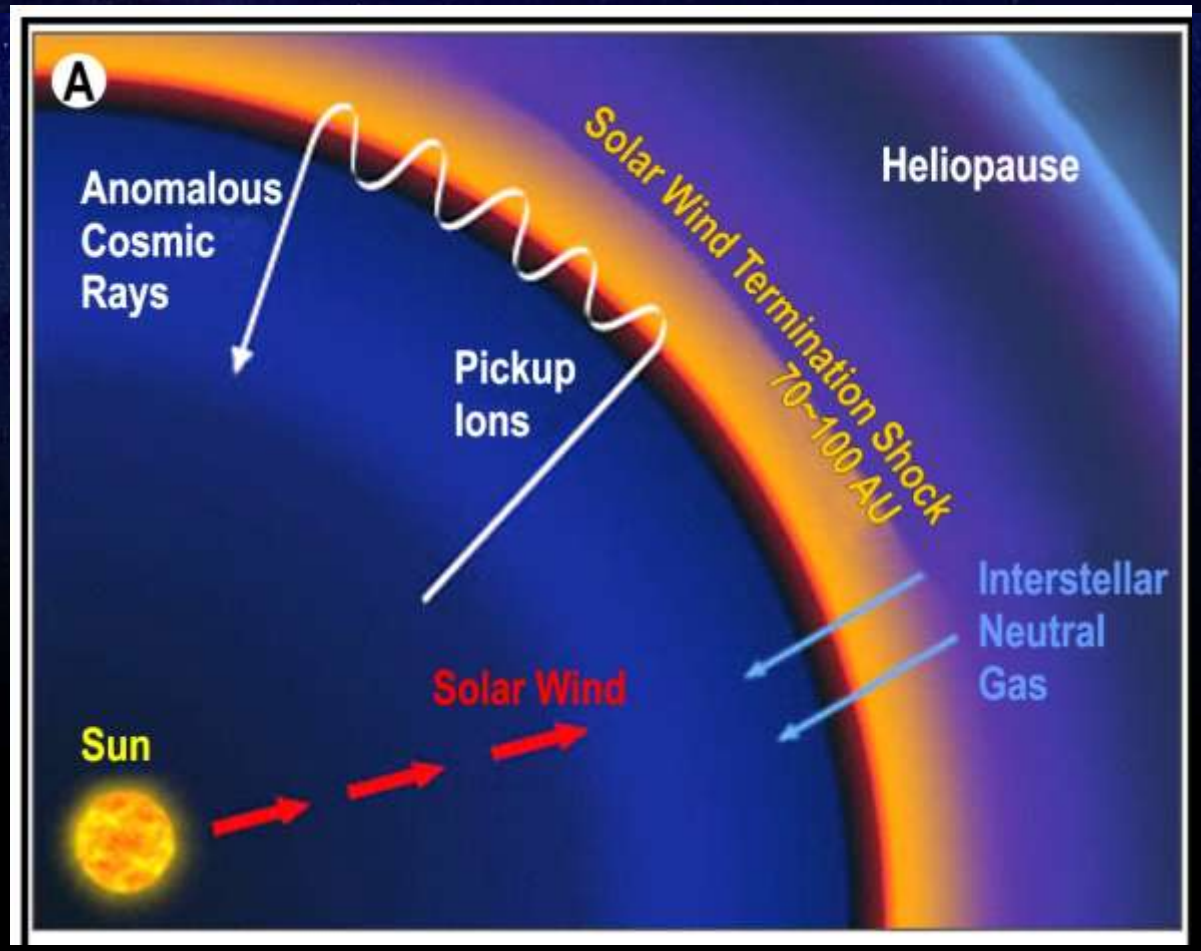




- Secondary CRs from air showers
- Detected in neutron monitors

Anomalous Cosmic Rays

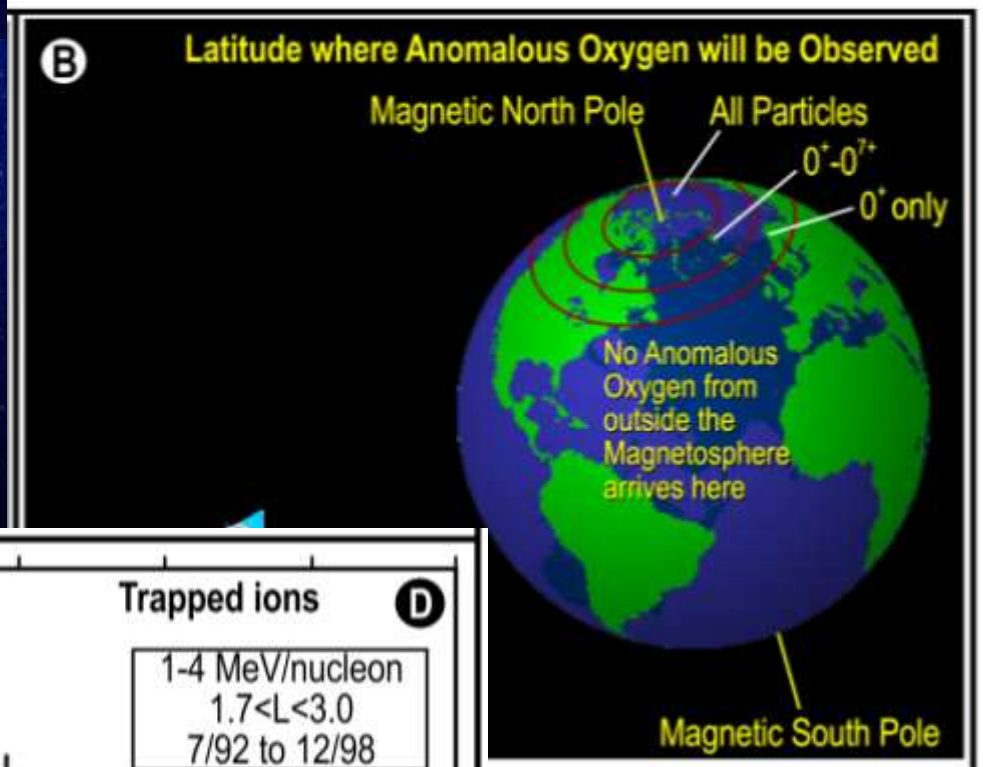


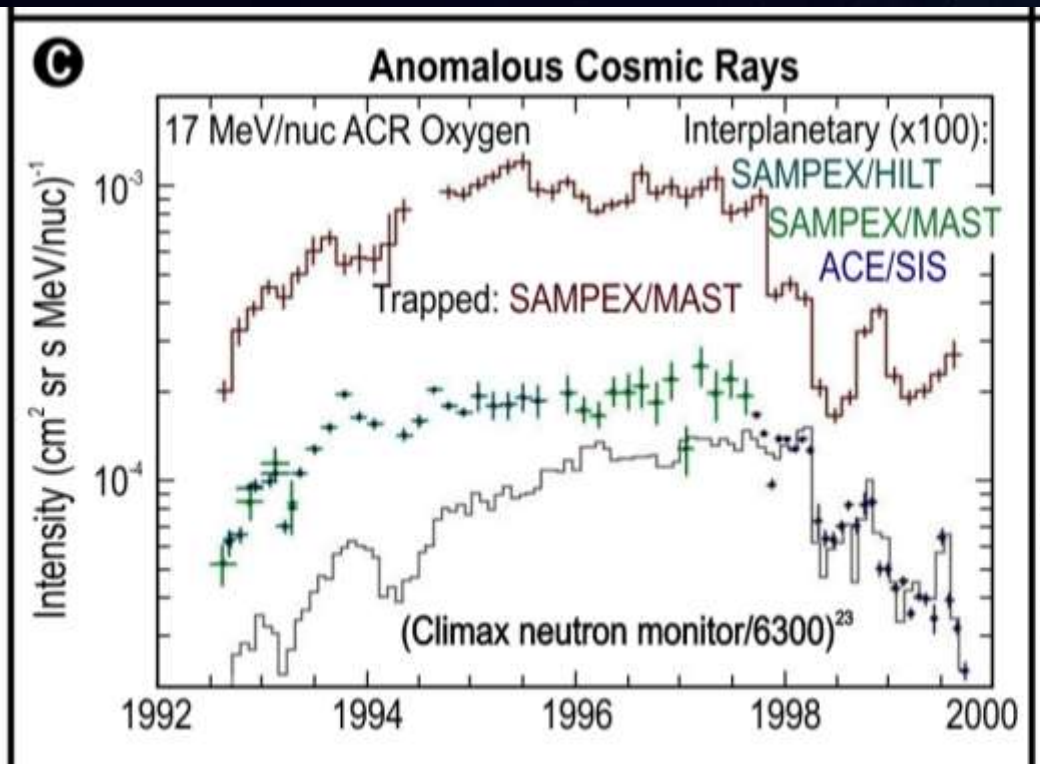


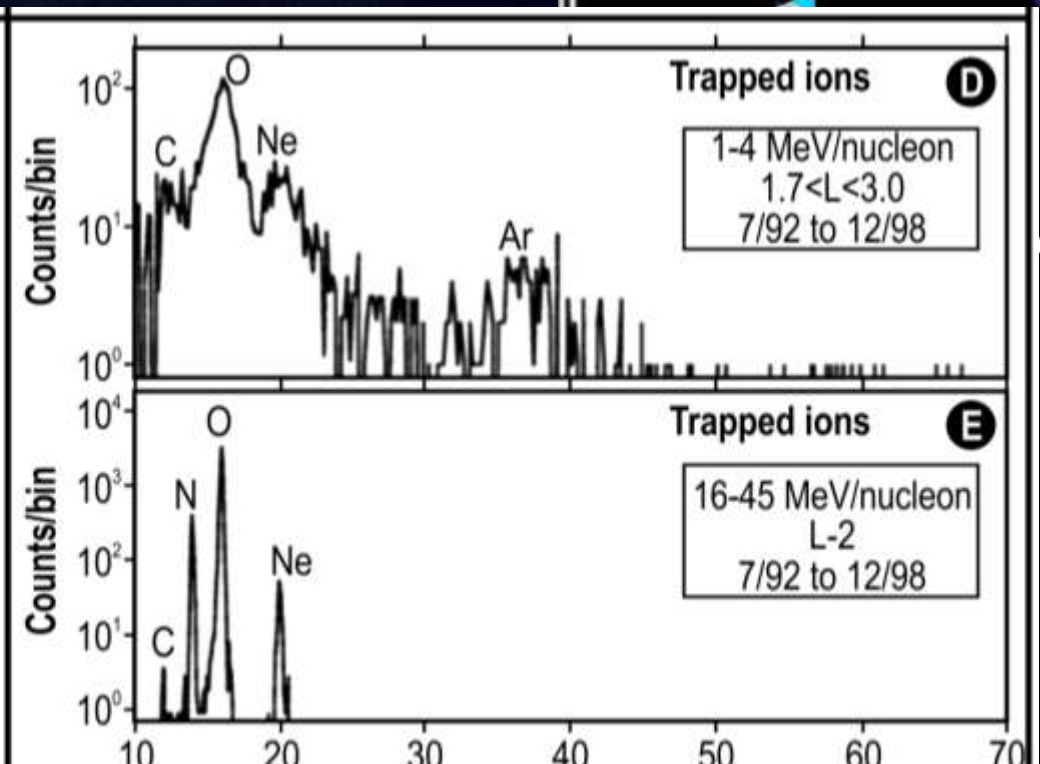
- Interstellar neutrals are ionized, and get convected ("picked-up") to the termination shock by the solar wind
- En-route they get accelerated by shocks, turbulence etc.
- At the termination shock, they get accelerated to 100s of MeV
- Propagate back into the inner solar system, measured near

ACRs in Geospace

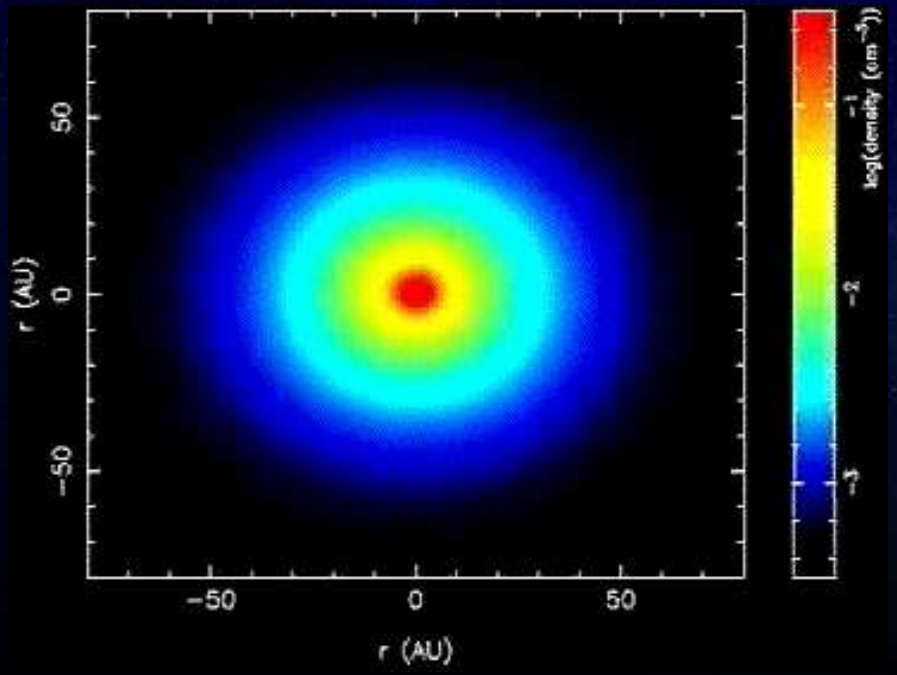
- Inside the heliosphere, ACRs also undergo similar modulation processes as GCRs
- Since ACR ions are singly charged they gain access to lower latitudes
- Here they remain trapped and can be observed by polar orbiting satellites like SAMPEX



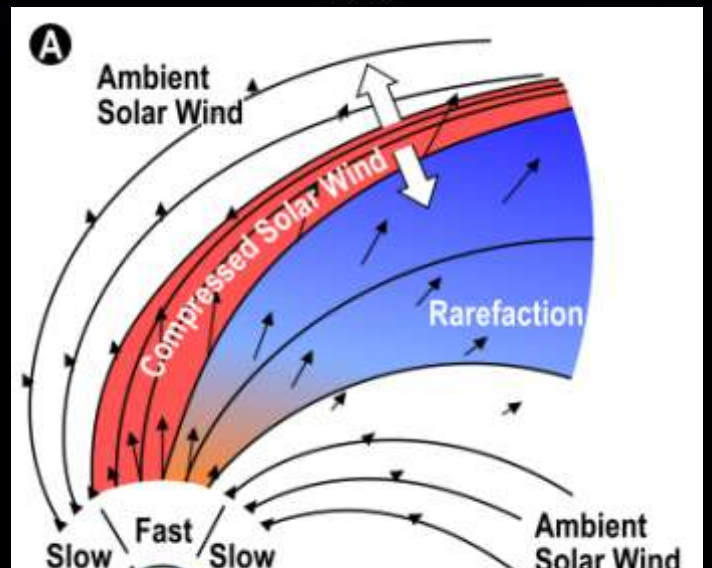


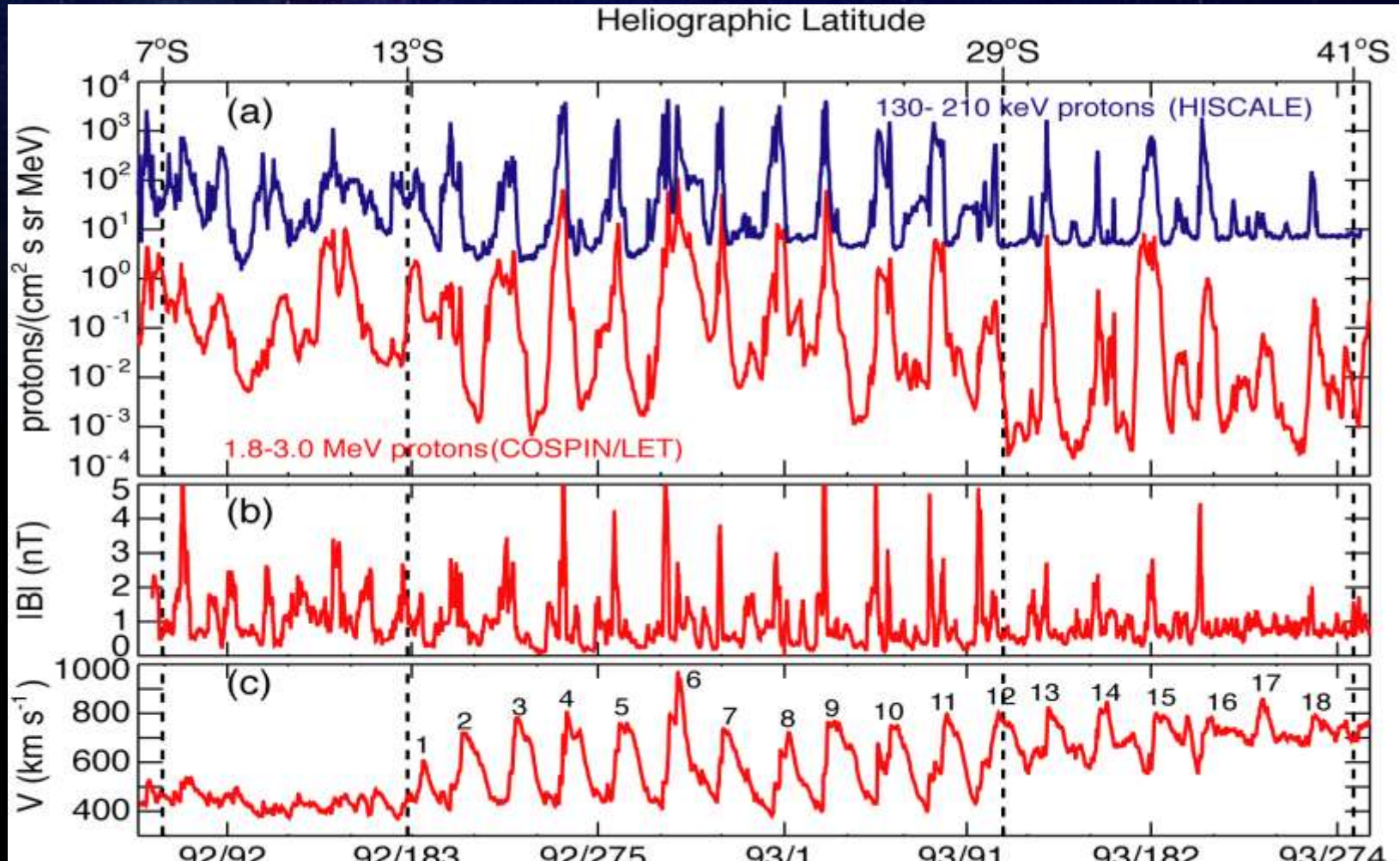


Corotating Interaction Regions

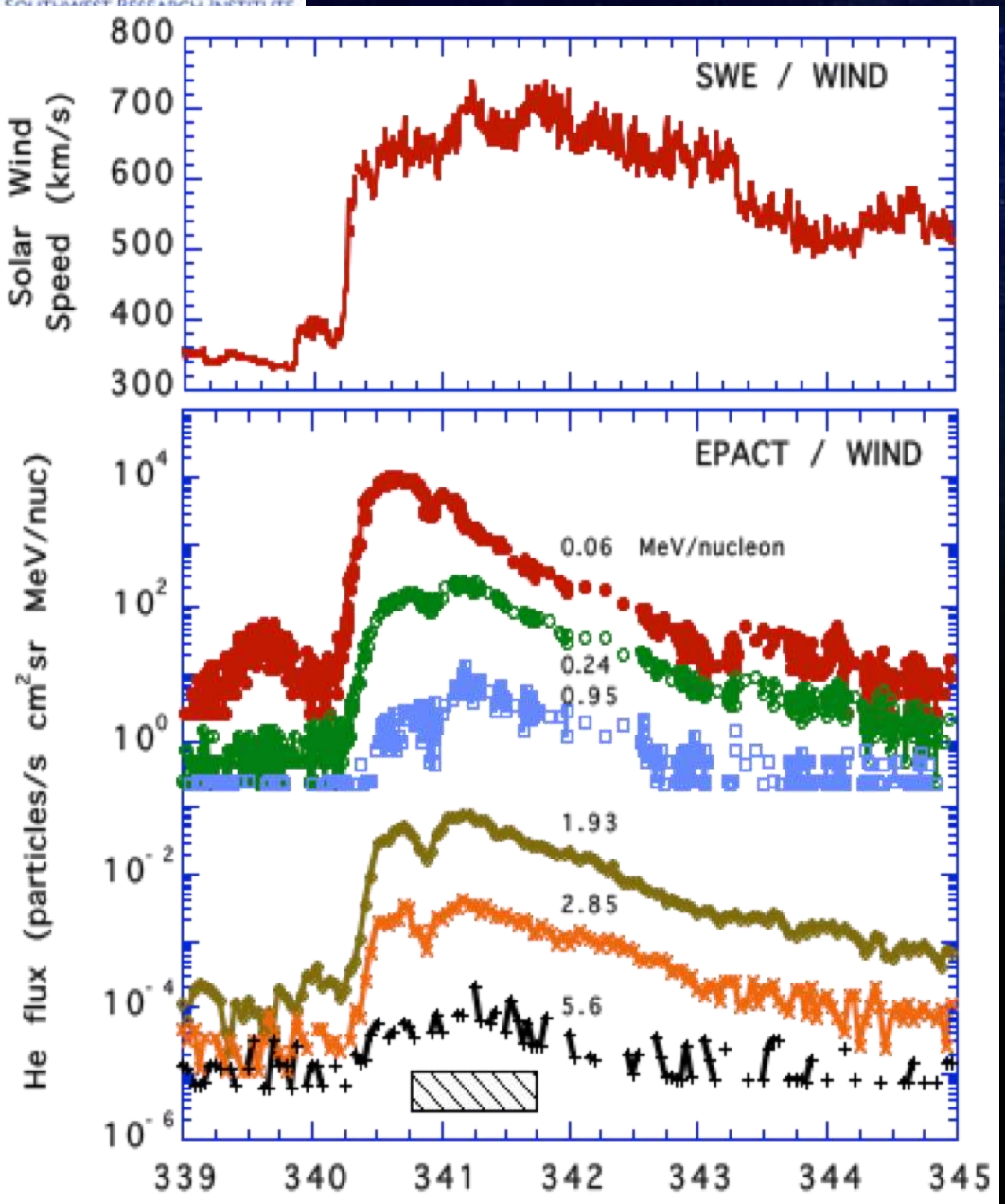


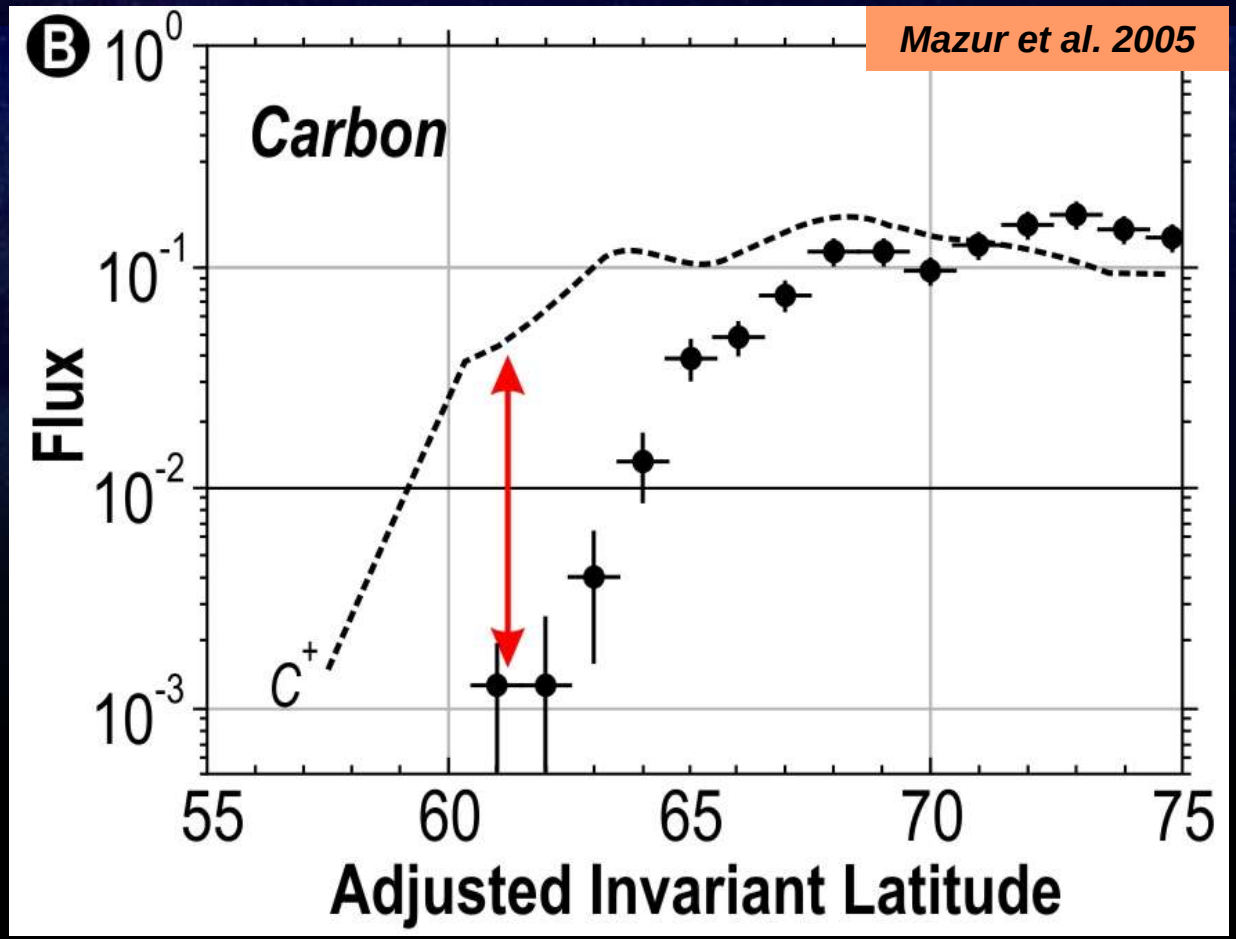
- Stronger inside 10 AU
- Bounded by forward-reverse shocks between ~2-5 AU
- Energetic Protons recur ~26 days





CIR Flux at 1 AU vs. Invariant Latitude



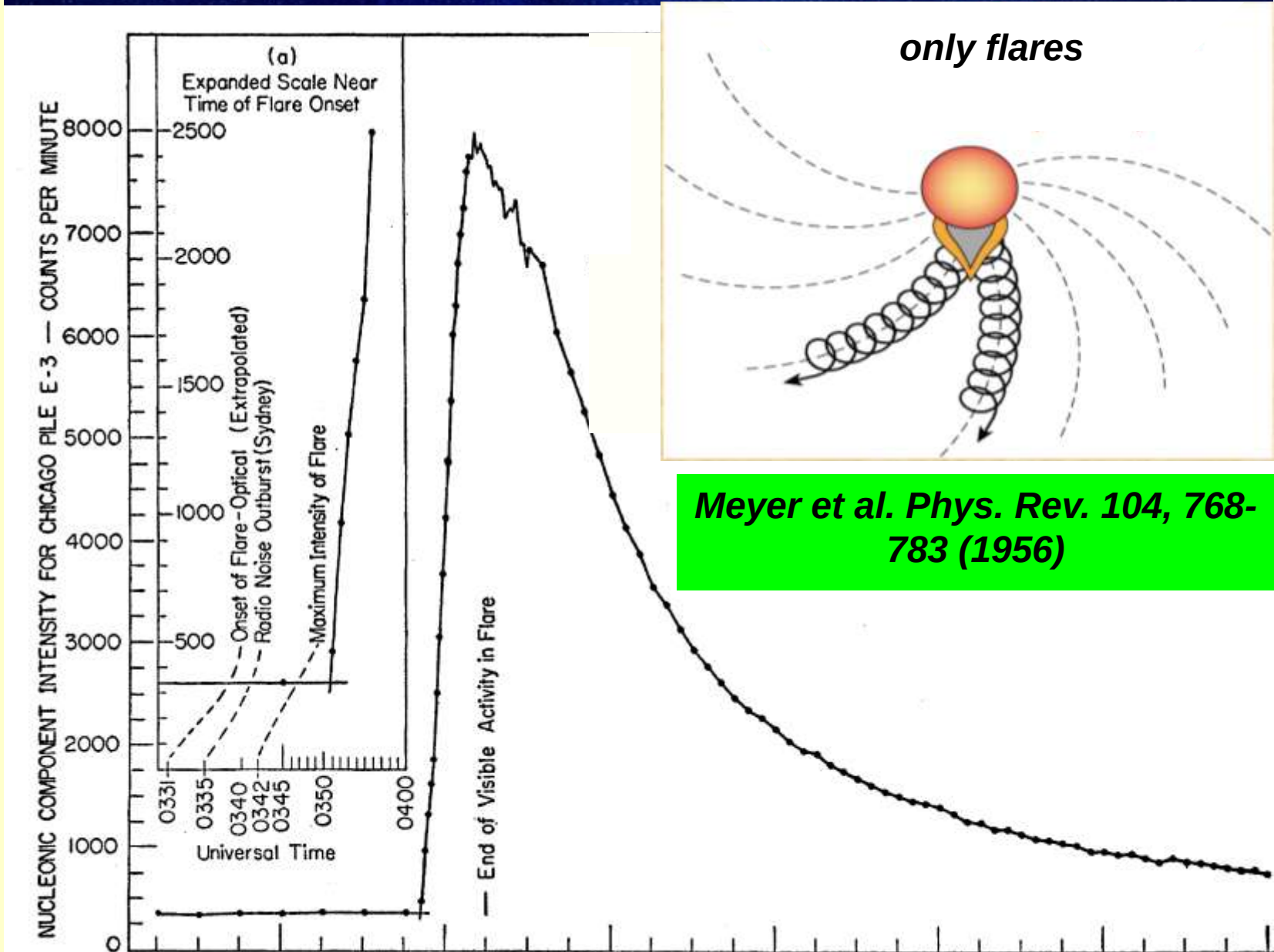


- Shocks typically not yet formed
- Observe particles with sunward anisotropies in the fast solar wind for several days
- Connection to reverse shock beyond 1 AU

Solar Energetic Particles - 50's-70's

- ***First observed from ground based ion counters (Forbush 1946)***
- ***Cosmic ray intensity increases associated with radio blackouts and solar flares***
- ***Closely related to Hα flares - (Meyer 1956)***

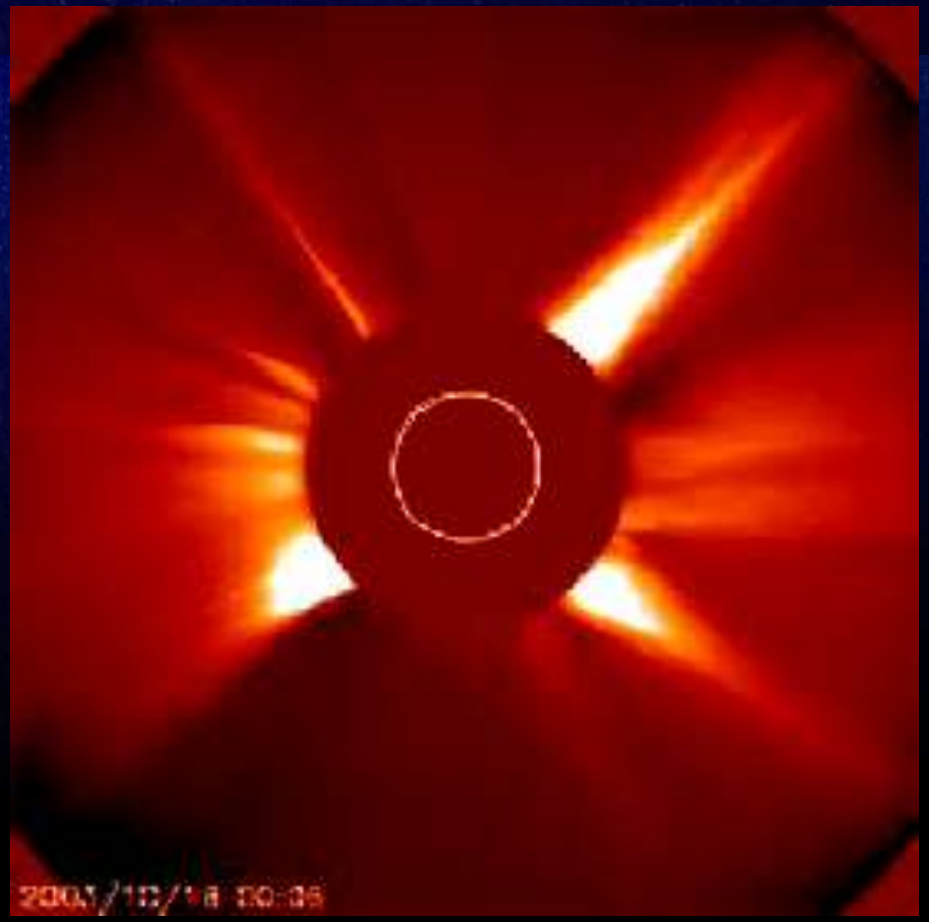
➔All SEPs at 1 AU are accelerated in solar flares



Meyer et al. Phys. Rev. 104, 768-783 (1956)

Solar Flares & CMEs

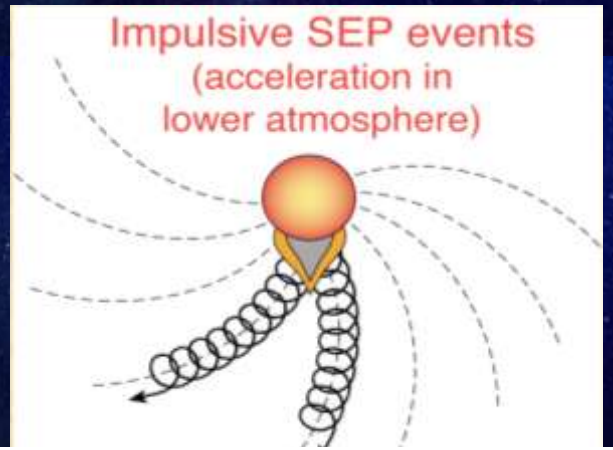
- Release ~10^{32} ergs in energy
- Plasma heated to ~10MK
- Accelerate particles
  - electrons to >100 MeV
  - ions to >1 GeV.
- Magnetic energy released in the solar

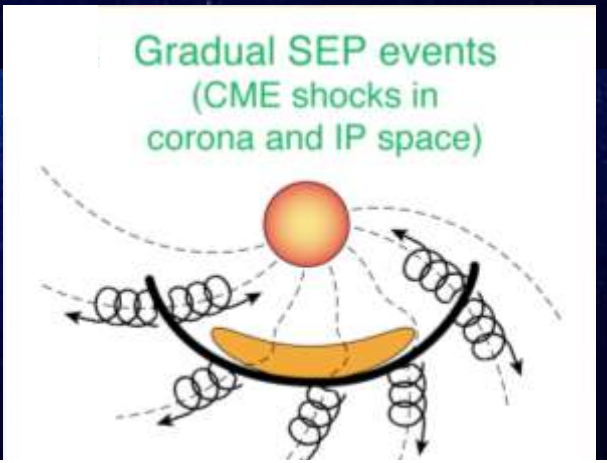


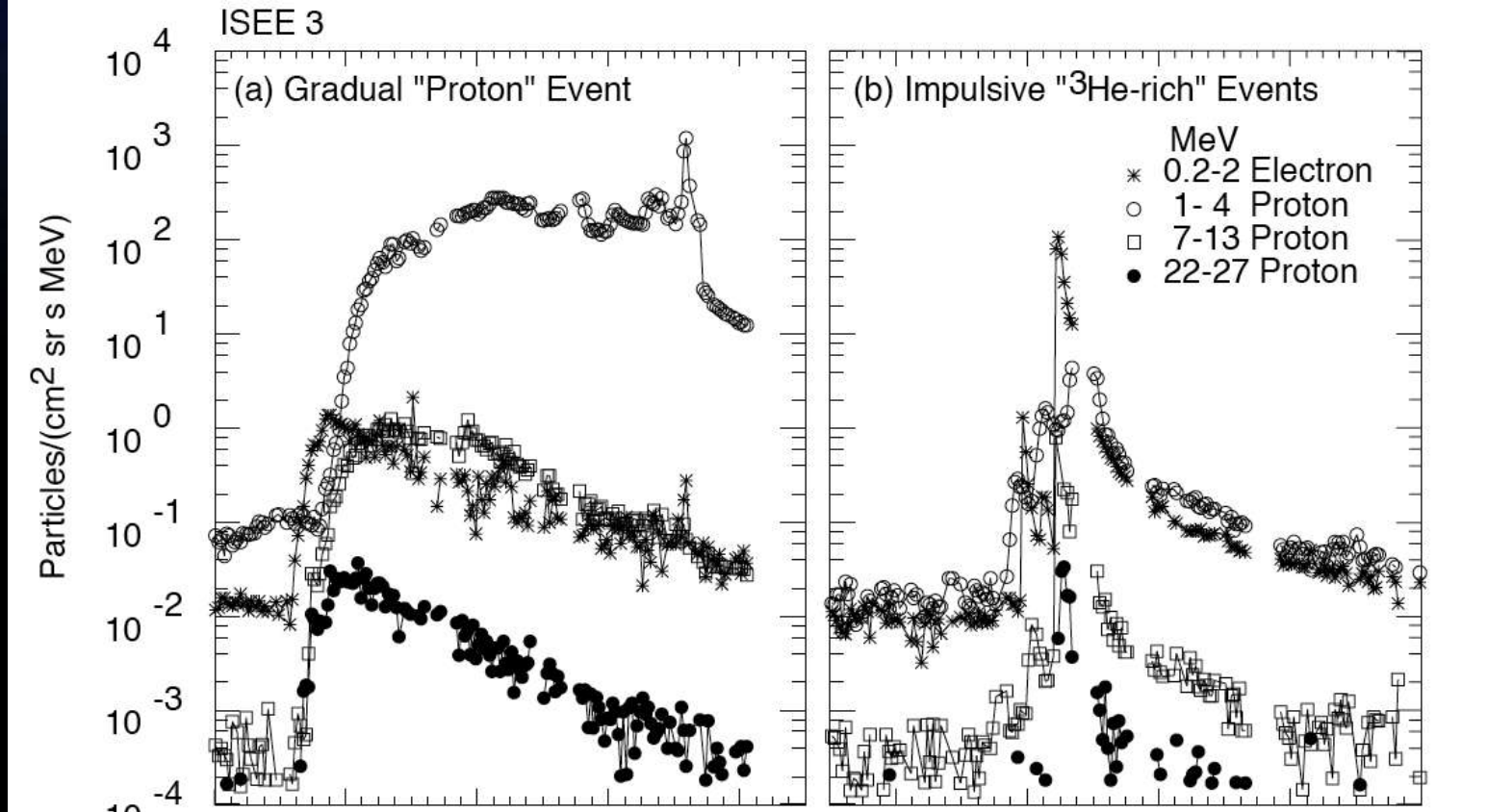
- CMEs drive fast shocks in the corona and interplanetary medium
- Shocks accelerate particles
  - electrons to >1 MeV (?)
  - ions to >1 GeV (?)

SEPs 70's - 90's => Two-Class Picture

- Large Gradual SEP events accelerated at CME-driven shocks
- ^{3}He-rich SEP events accelerated during flares via magnetic reconnection

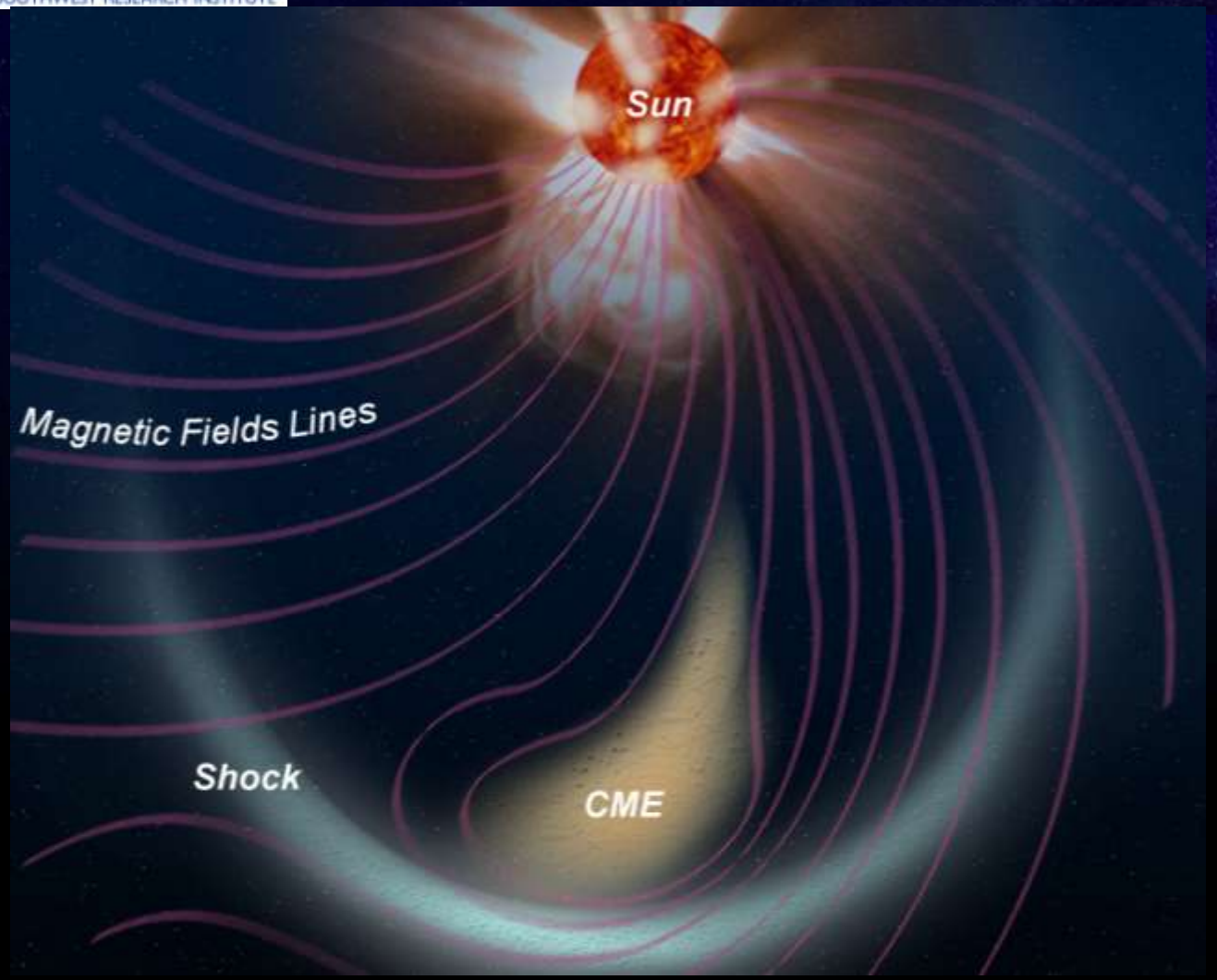


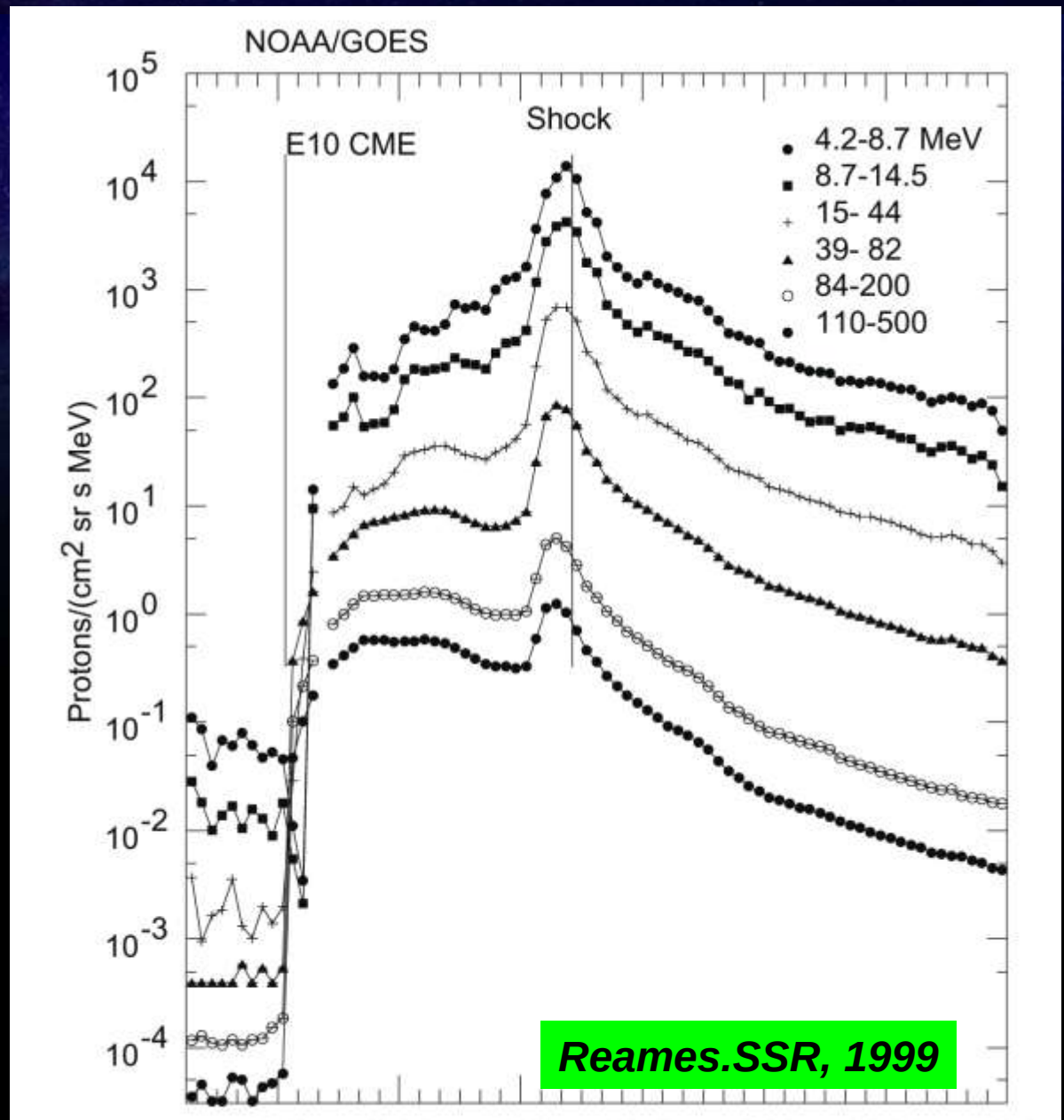




Wild et al. (1963)
Lin (1970)
Pallavacini et al (1974)
Kahler et al. (1978)
Mason et al. (1984; 1986)
Cane et al. (1986; 1988; 1991)

Double Whammy:SEPs from CME shocks



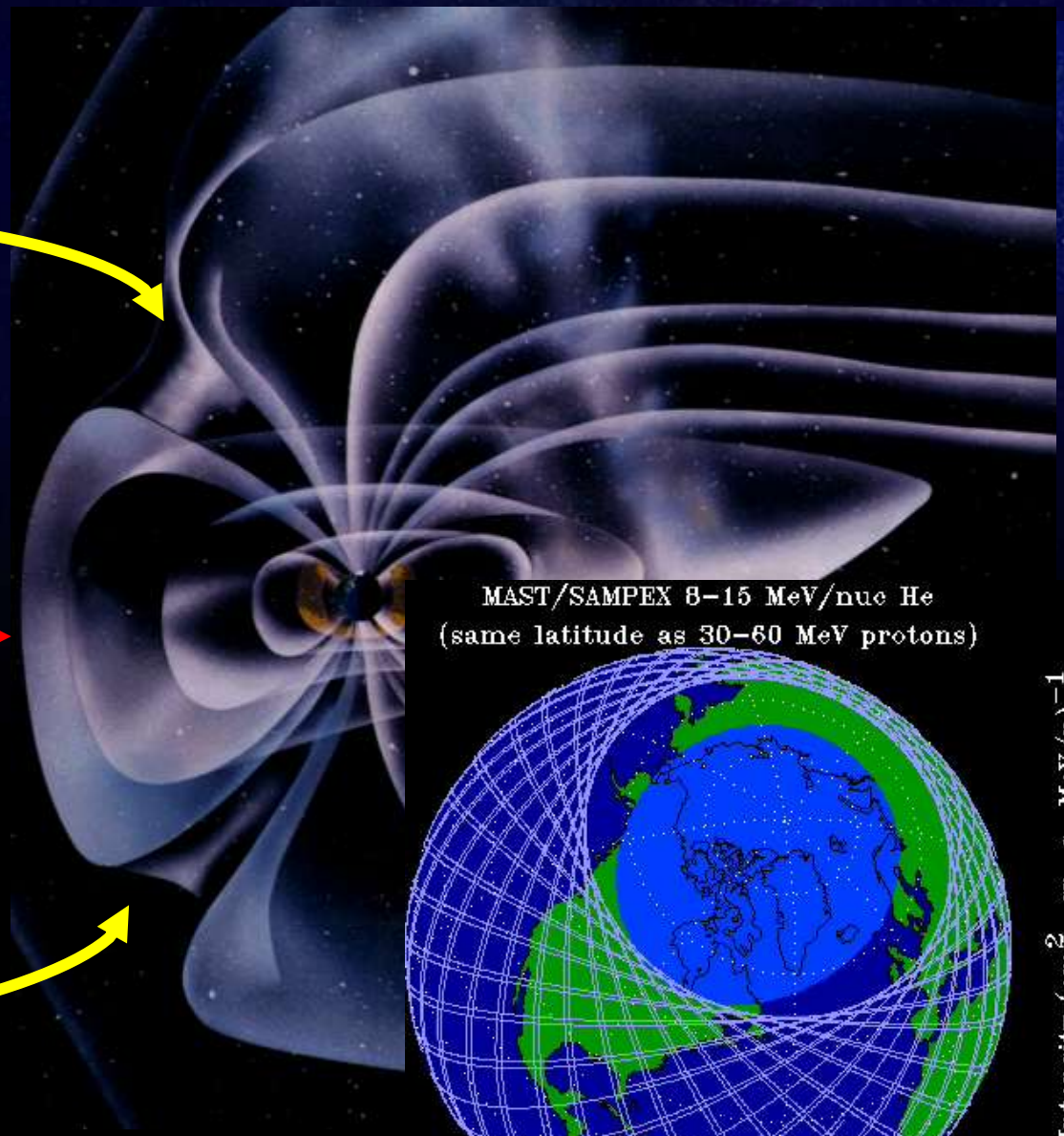


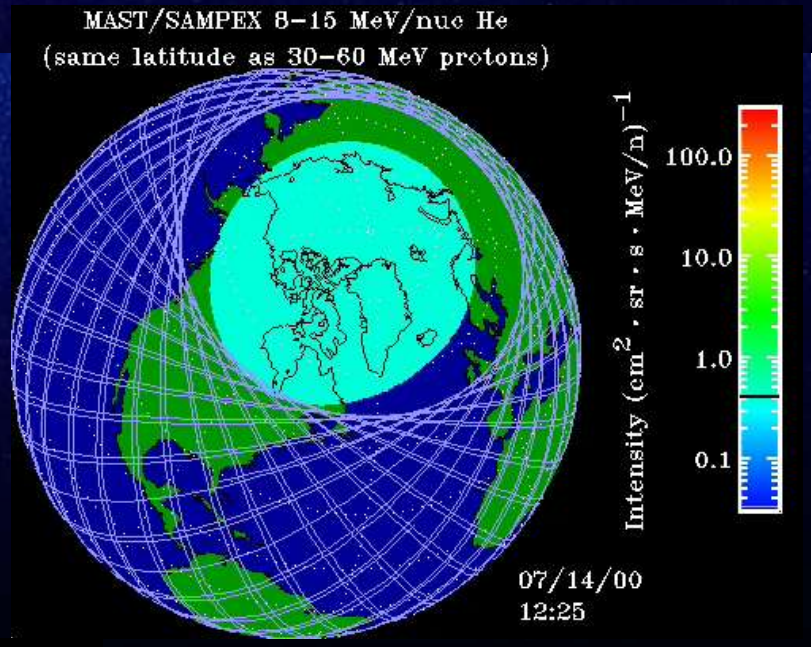
SEP Access to Geospace

Open

"Closed"

Open

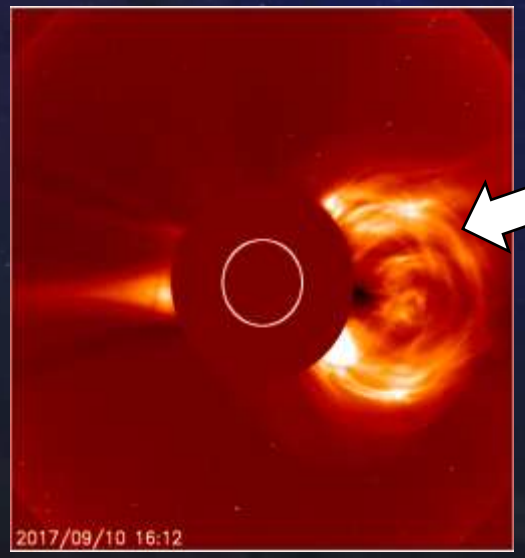




- Invariant Latitude changes with time
- SEPs gain access to lower latitudes
- Geospace Impacts

Solar Protons up to 1 GeV in the 9/10/17 CME Event

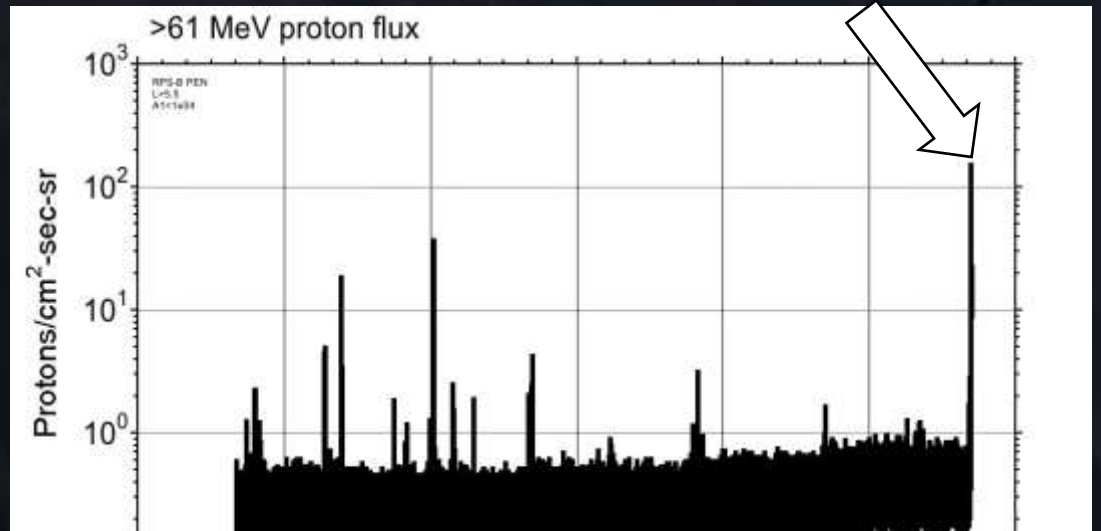
From Joe Mazur, Aerospace Corp



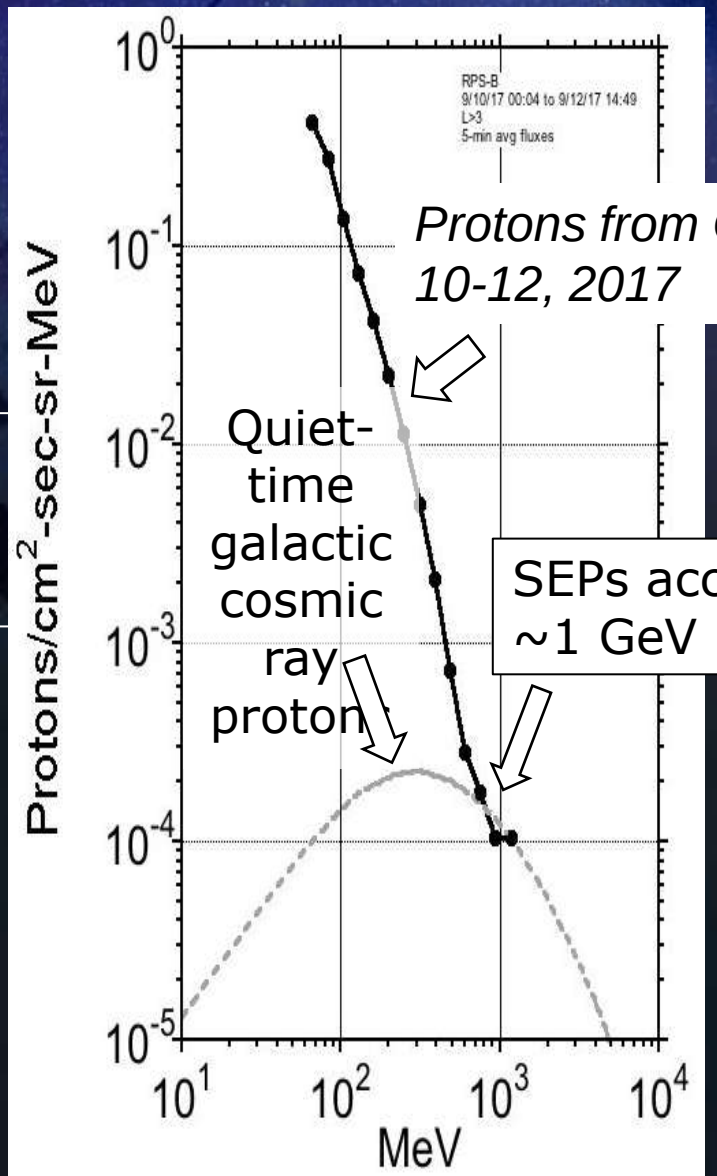
CME liftoff: 9/10/17 1600UT
Estimated speed: 1081 km/s

www.spaceweather.gmu/edu

Most intense solar proton event >60 MeV seen during the Van Allen Probes mission



Van Allen Probes/RPS-B Proton Energy Spectrum

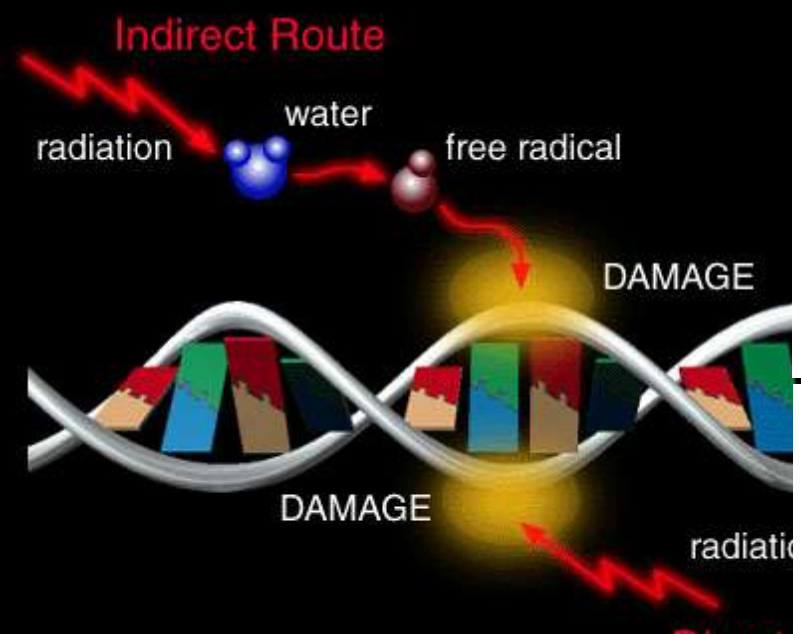


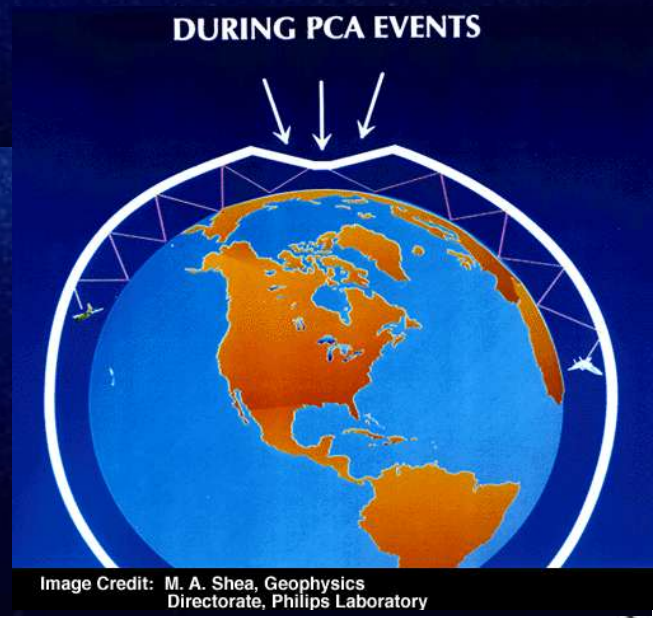
Protons from CME shock Sept 10-12, 2017

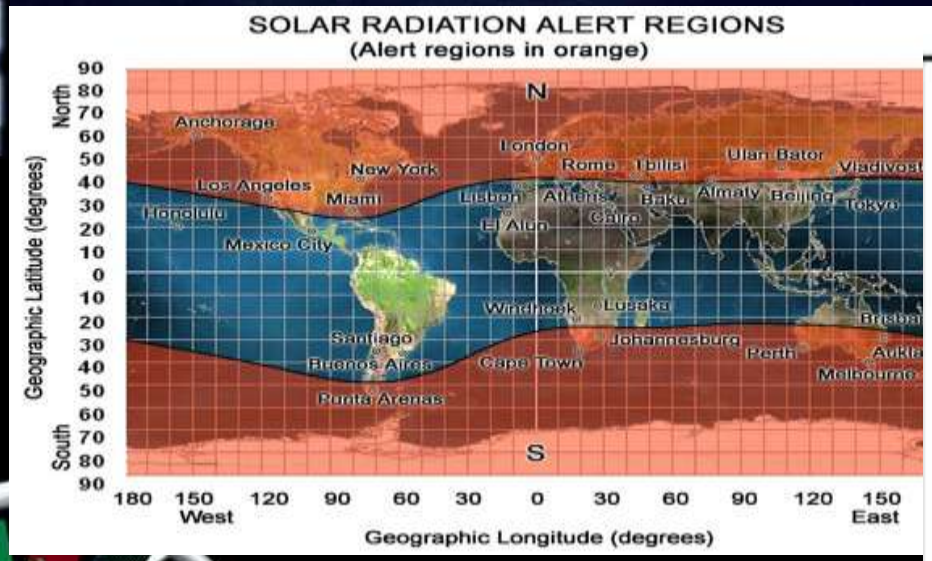
SEPs accelerated to ~1 GeV

SEP Geopsace Impacts

- ISS Astronauts
- Airline Crew/Passengers
- Spacecraft SEUs
- Radio communication

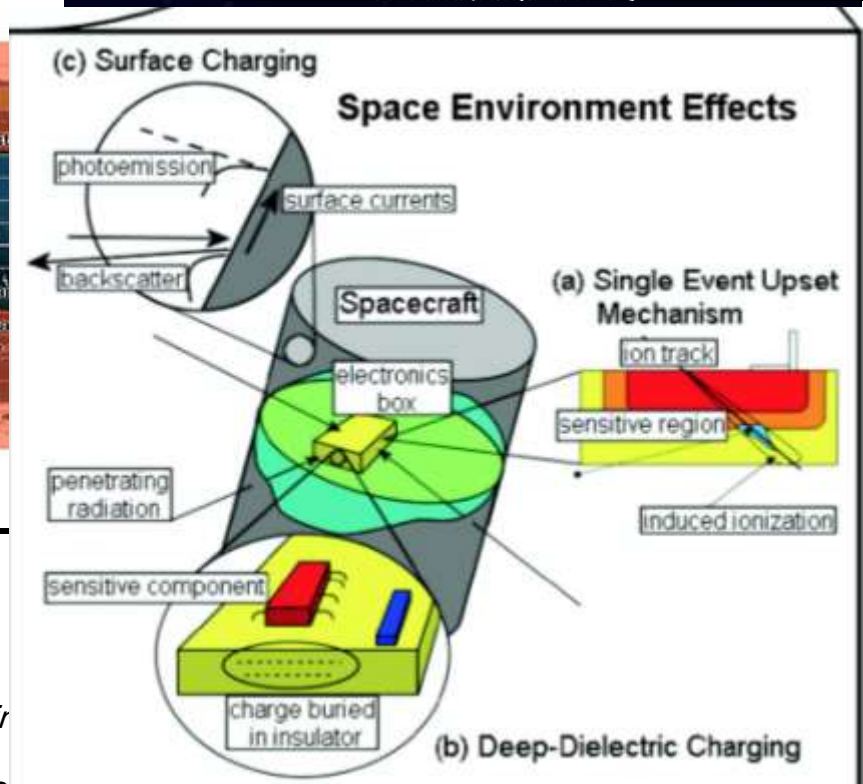






Issue Time: 2003 Oct 28 2123 UTC
ALERT: Solar Radiation Alert at Flight Altitudes
Conditions Began: 2003 Oct 28 2113 UTC

Satellite measurements indicate unusually high levels of ionizir radiation coming from the Sun. This may lead to excessive



Summary

- MeV protons and ions from a variety of heliospheric ion populations can enter the Earth's magnetosphere
- GCRs, ACRs, and CIR-associated particle events occur during solar minimum conditions, while SEPs/ESPs occur primarily during solar maximum
- Only GCRs and SEP/ESP ions are of primary Space Weather concern
- GCRs have low fluxes, are highly ionizing, can create air showers and secondary radiation that can affect Earth's atmosphere
- SEPs have higher fluxes, are a radiation hazard to ISS Astronauts, Airline Crew/Passengers on polar routes, can cause single event upsets in spacecraft systems, and HF radio communication