The origin and propagation of Solar Energetic Particles and their impact on Earth

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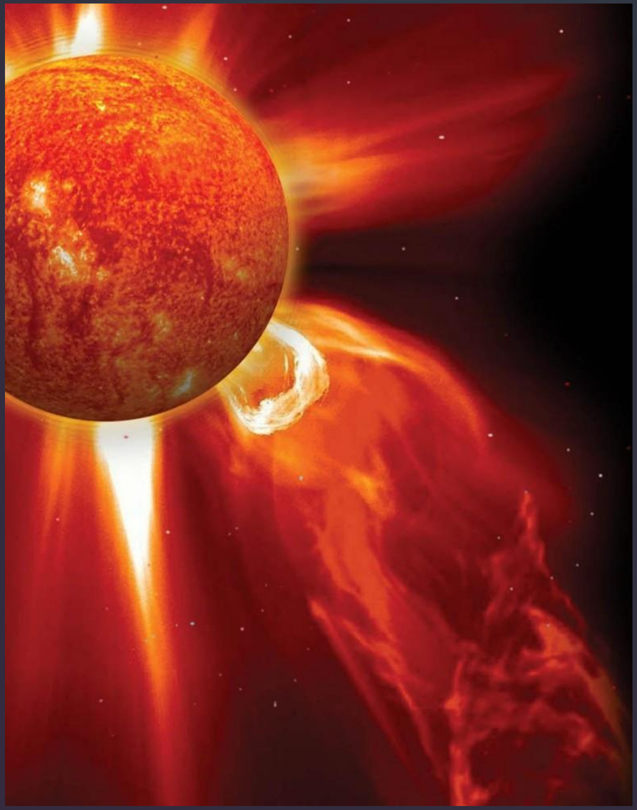
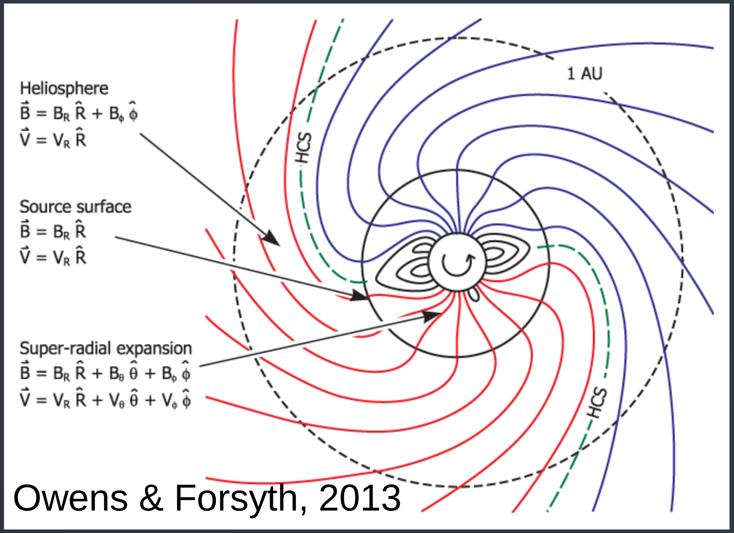
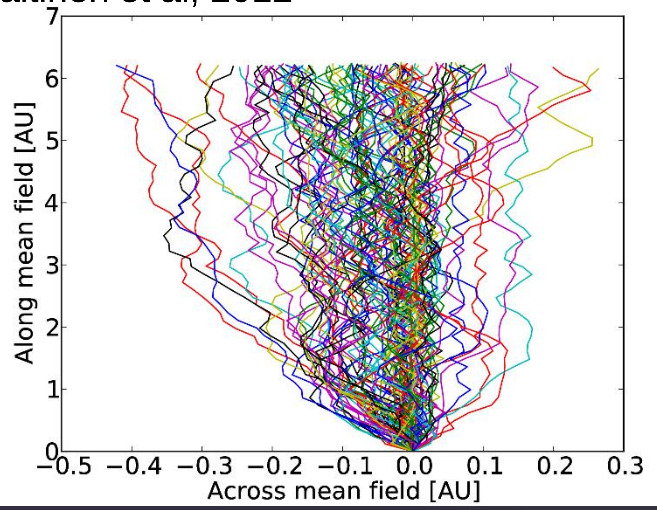
The problem

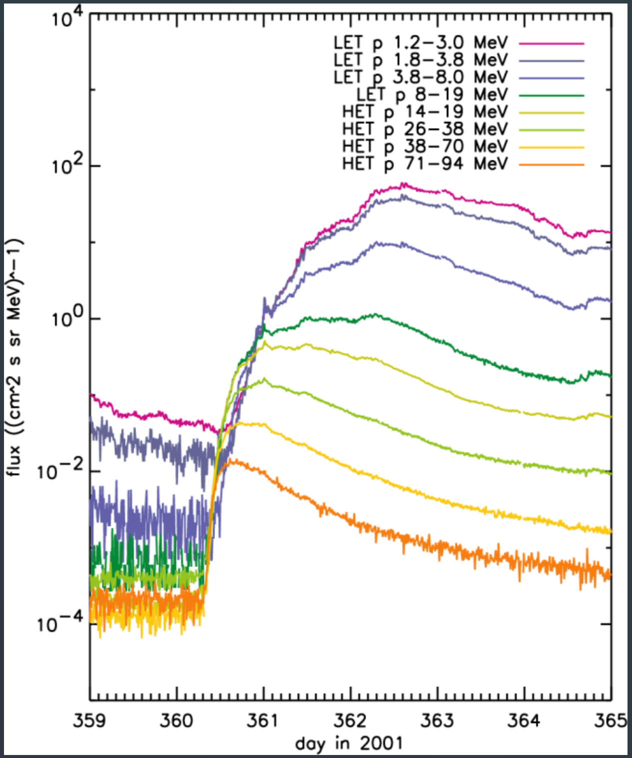




Owens & Forsyth, 2013

Laitinen et al, 2012



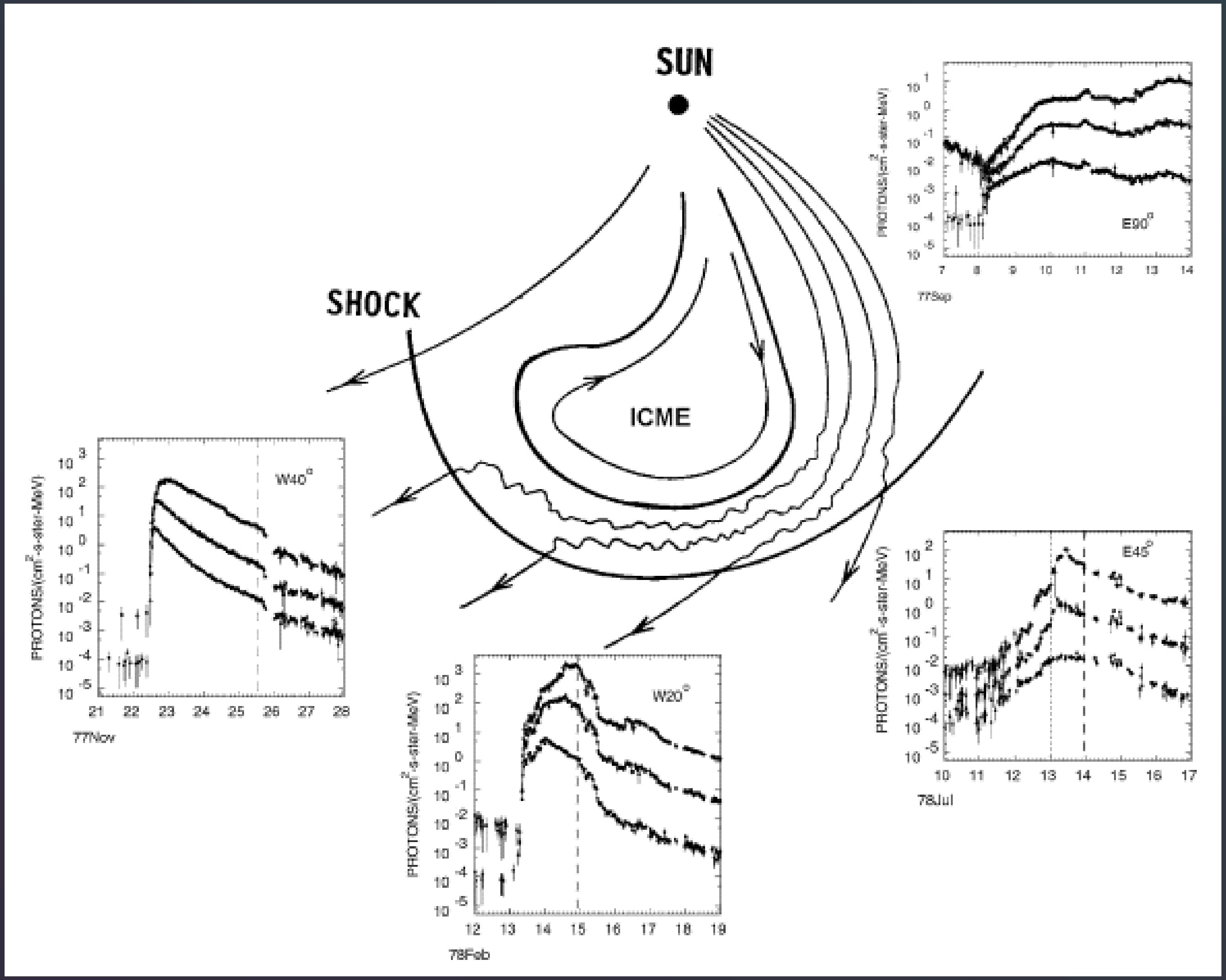


Outline

- Key observations and impact
- 2-class paradigm
- Interplanetary propagation
- Approaches to modelling for Space Weather

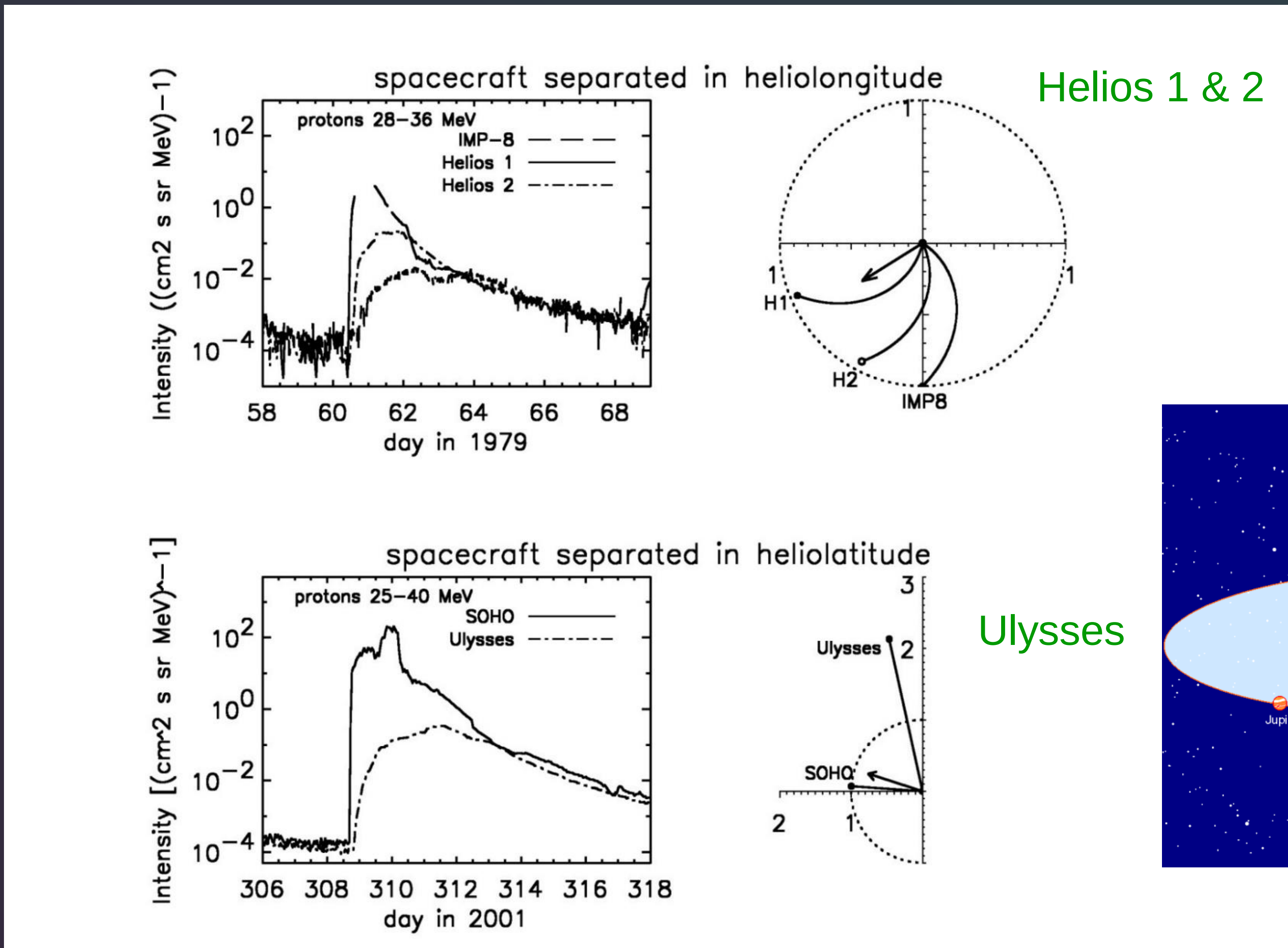
Key observations and impact

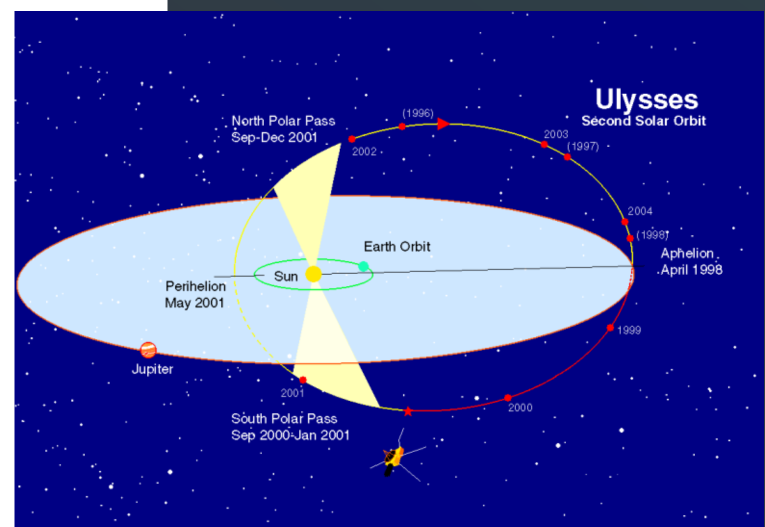
East-West variation of intensity profiles



Adapted from Cane et al, 1988

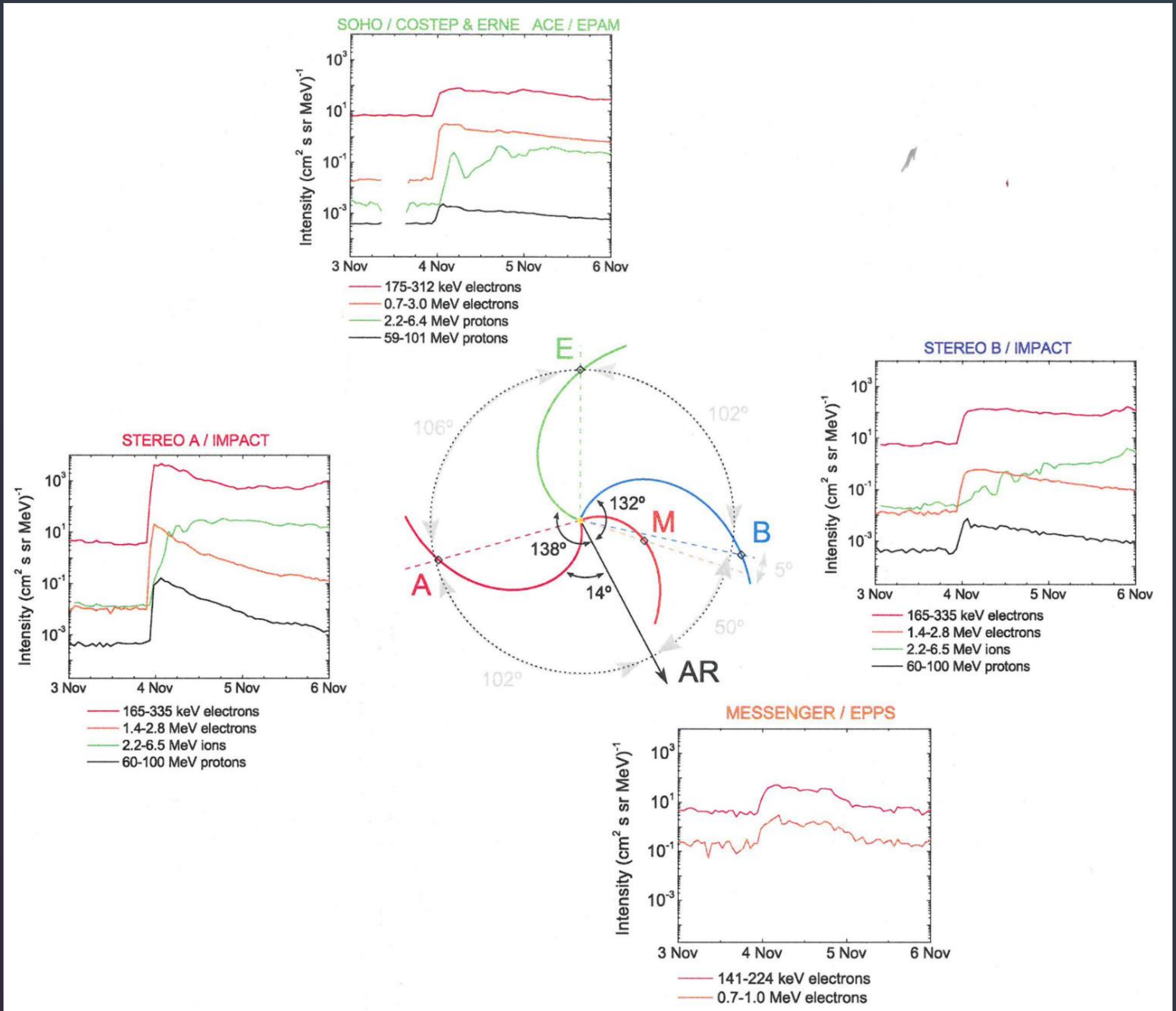
Heliolongitude/heliolatitude variation





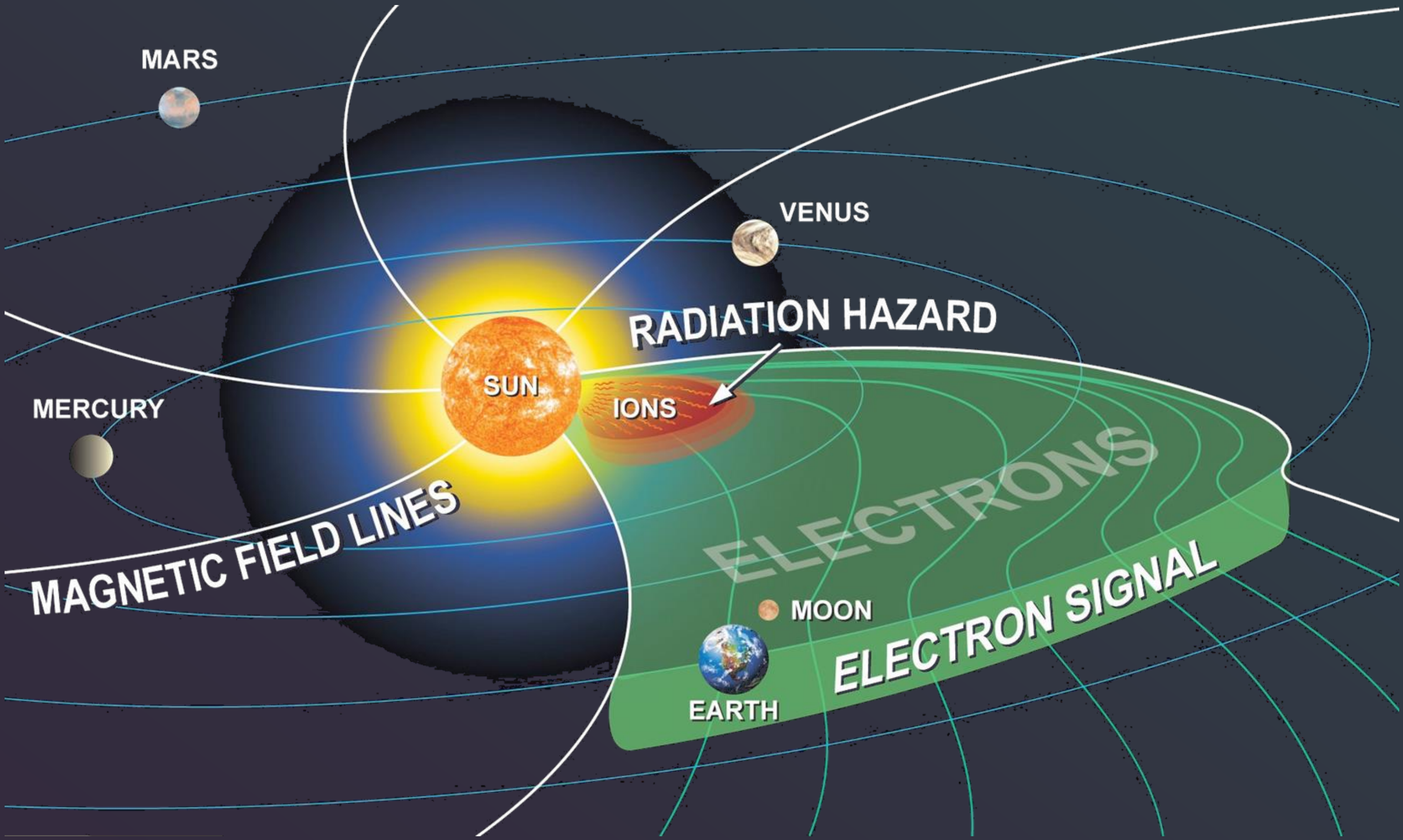
Klecker et al, 2006

360° SEP event



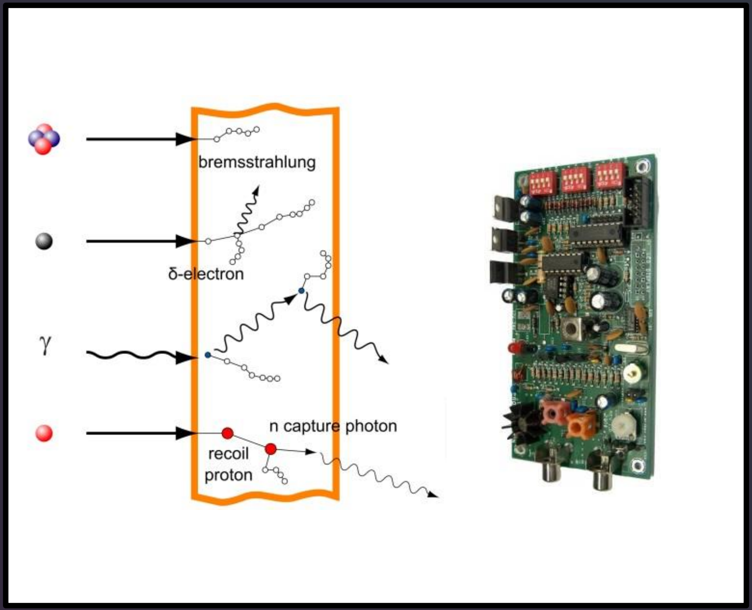
Gomez-Herrero et al, 2015

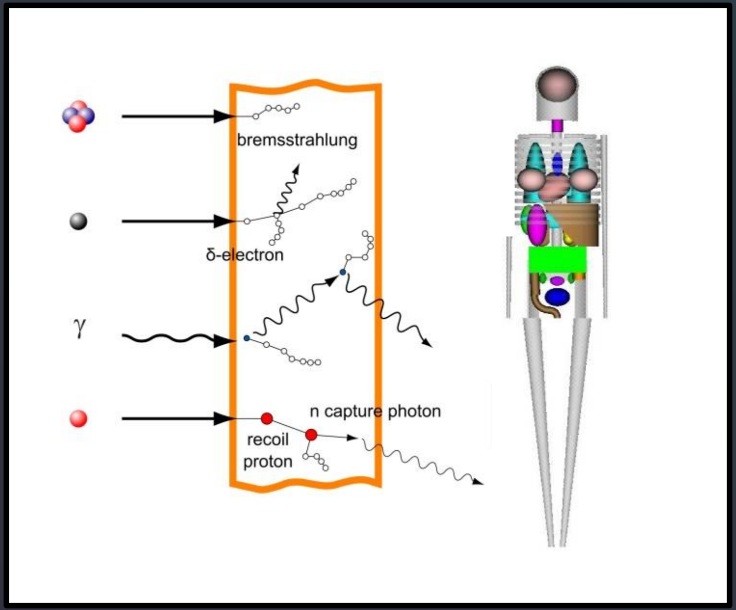
Impact


MARS
VENUS
RADIATION HAZARD
SUN
IONS
MERCURY
ELECTRONS
MAGNETIC FIELD LINES
MOON
ELECTRON SIGNAL
EARTH

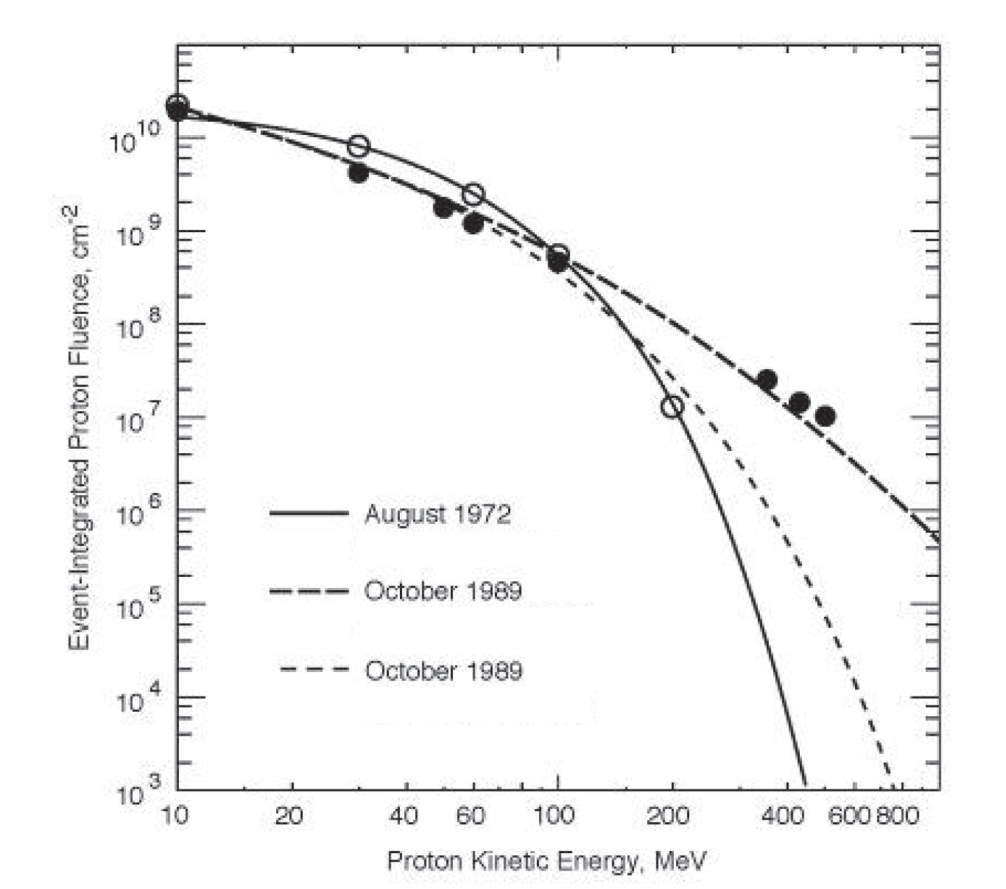
Impact scenarios

- Radiation effects on humans, electronic components on spacecraft
- Disruption to communications, effects on stratosphere and mesosphere





Radiation dose calculations

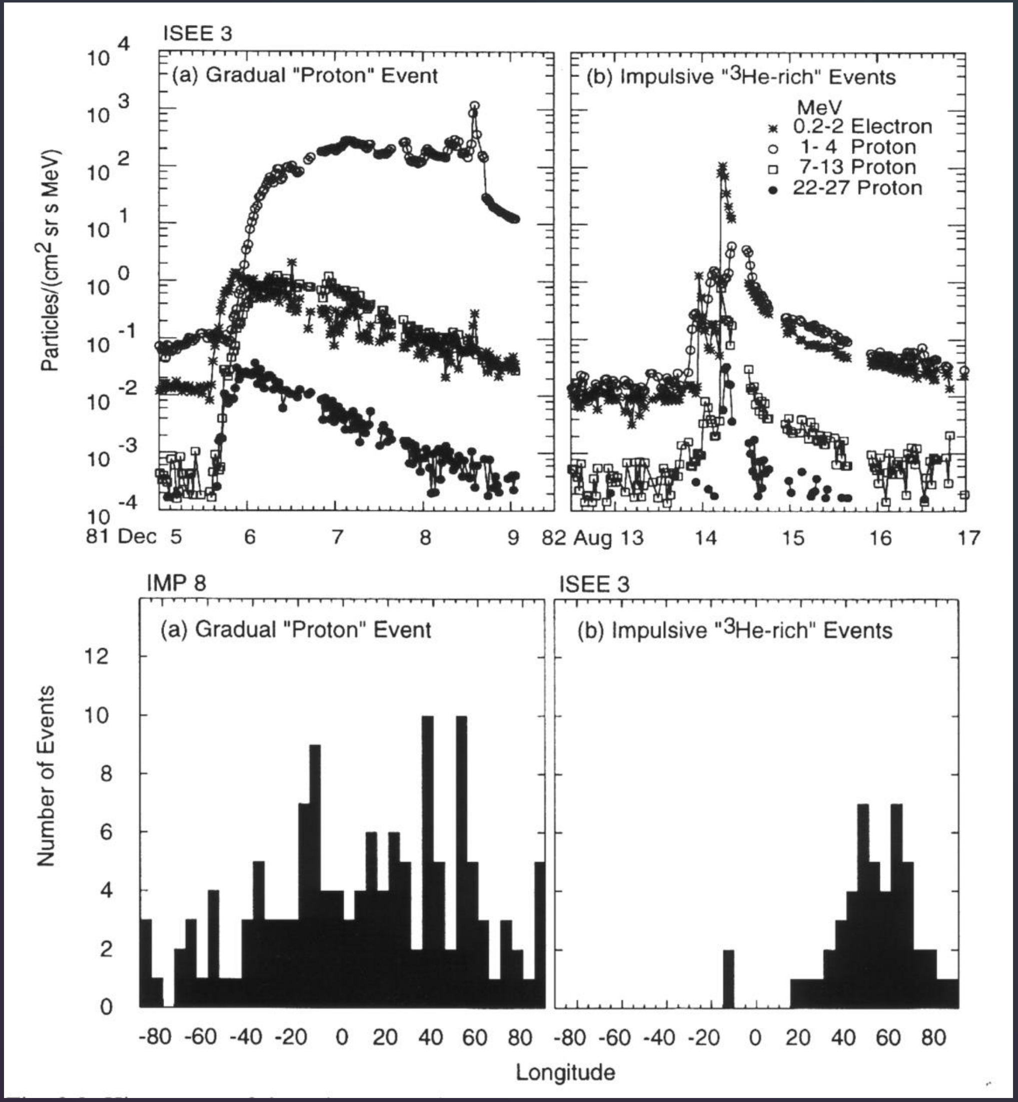


- information on SEP energy spectrum required up to high energies (ideally with time evolution)

US NRC Report on Space Radiation Risk in the New Era of Space Exploration, 2008

2-class paradigm

2-classes of SEP events



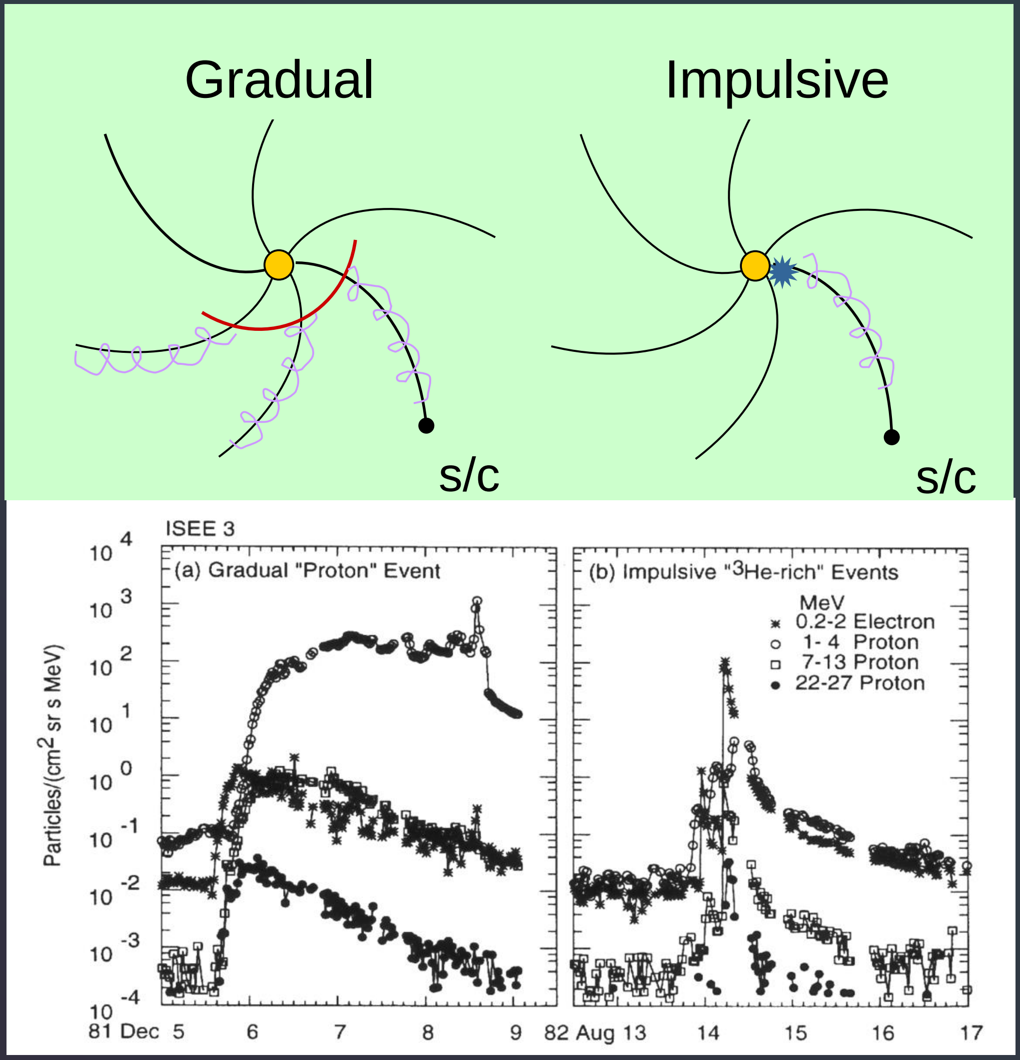
	Gradual	**Impulsive**
Event duration	days	few hours
Electron/proton	low	high
He 3 / He 4	coronal	coronal*1000
Longitude of solar event	any	W20-W90
Fe/O	coronal	coronal*10
Fe mean charge	15	20
Source of particles	***CME shock***	***Flare***

Reames, 1999

2-class paradigm

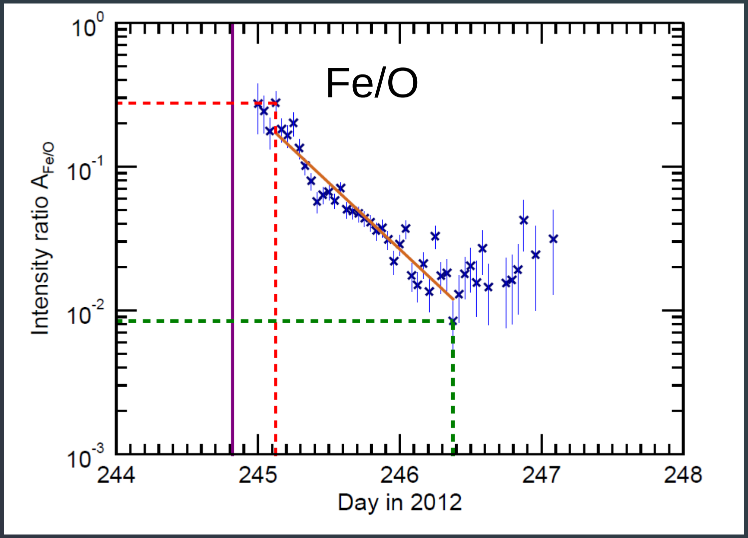
- Wide spread in longitude results from extended source: travelling CME-driven shock

- In this model, propagation is assumed to be 1D and SEP profiles are shaped mostly by acceleration process

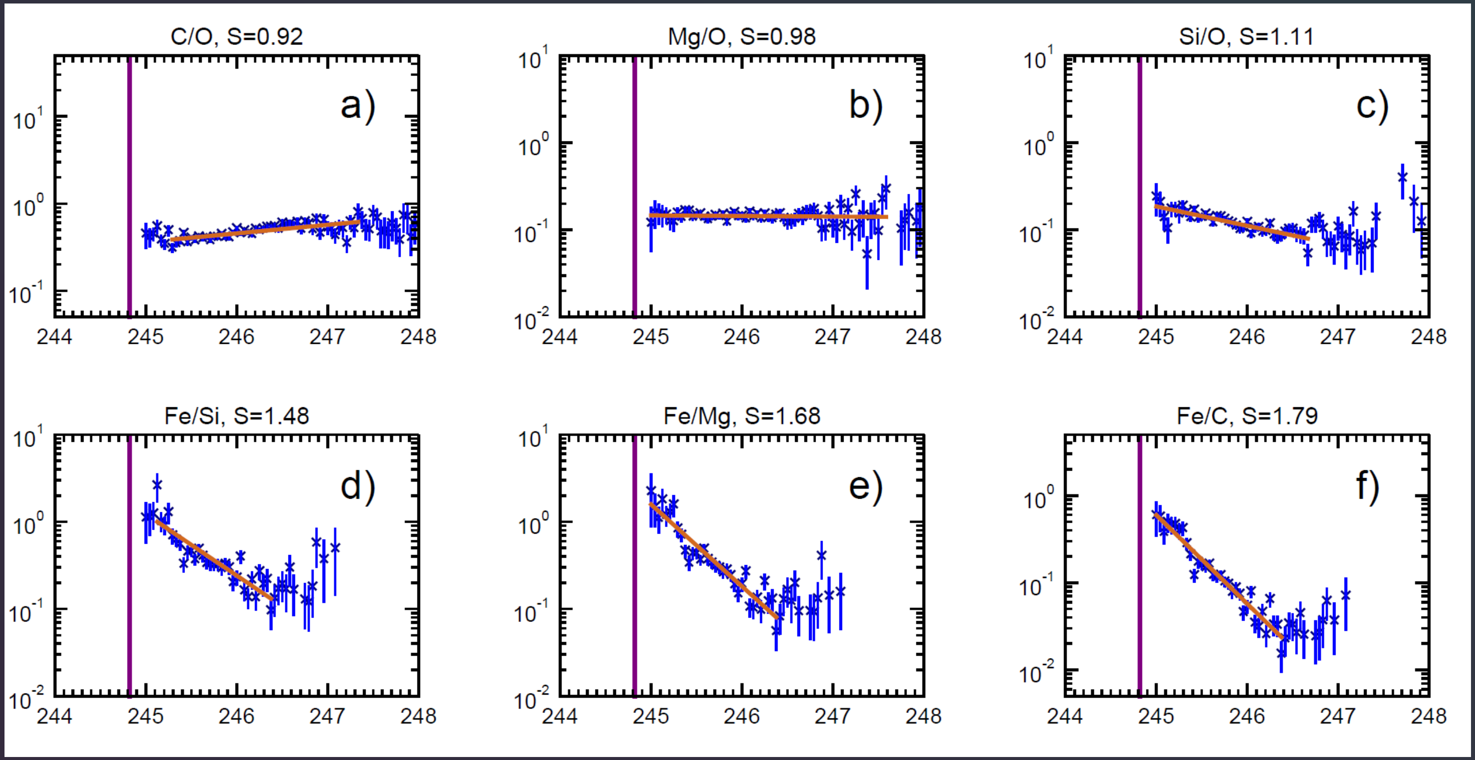


Reames, 1999

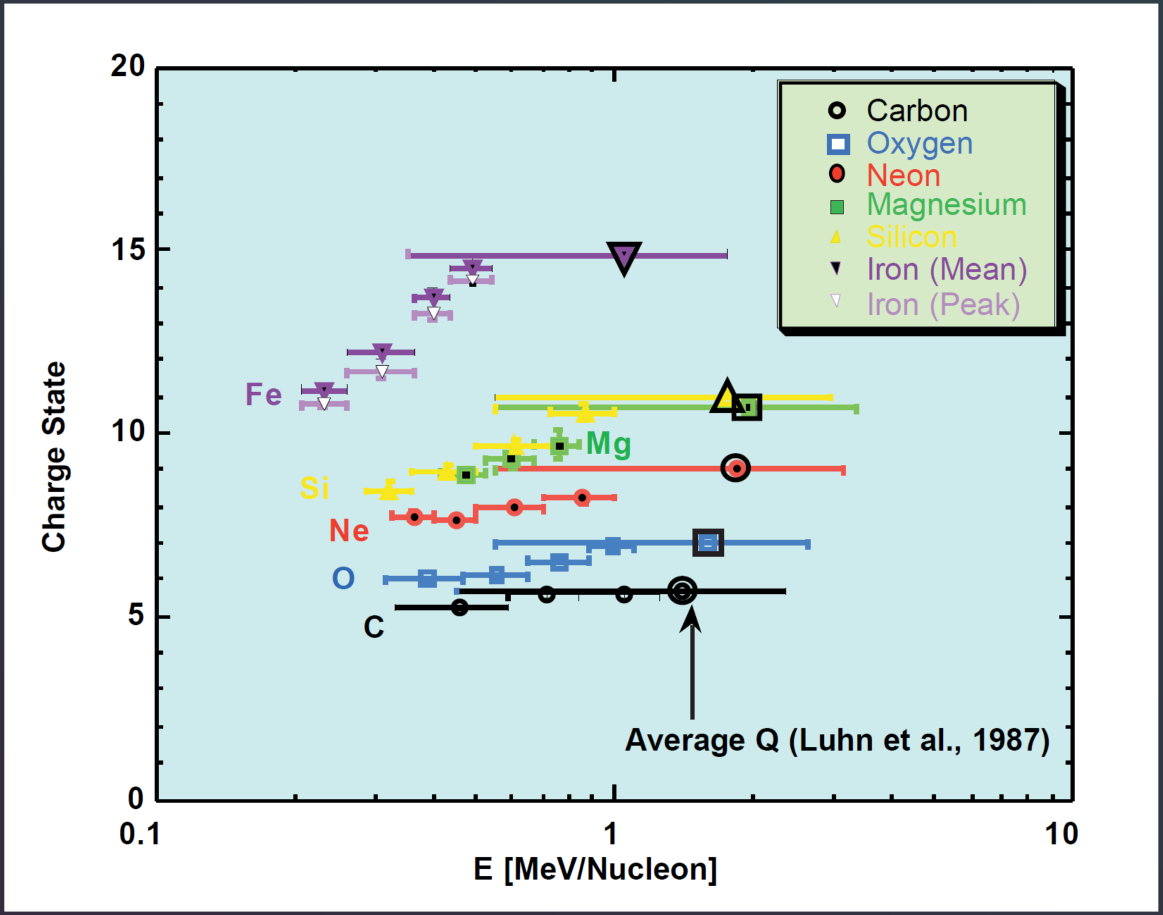
Time variation of ionic ratios



Zelina et al 2017



Energy dependence of charge states



Möbius et al, 1999

Interplanetary propagation

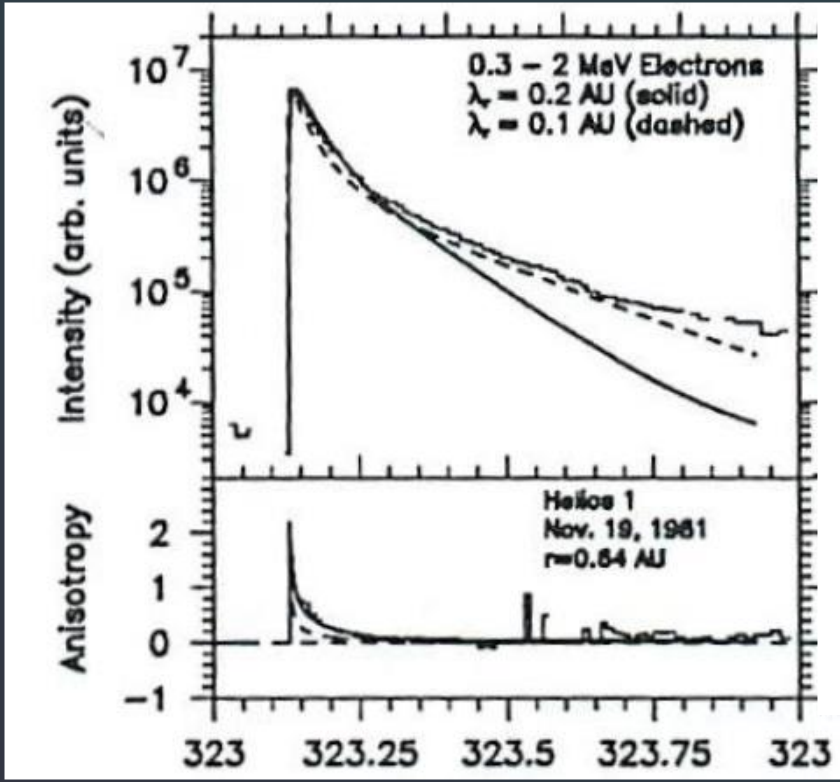
Transport models

- Classic description is kinetic, eg focussed transport equation

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial s} + \frac{1-\mu^2}{2\varsigma} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}(\kappa(\mu)\frac{\partial f}{\partial \mu}) = Q(r,v,t)$$

Roelof 1969

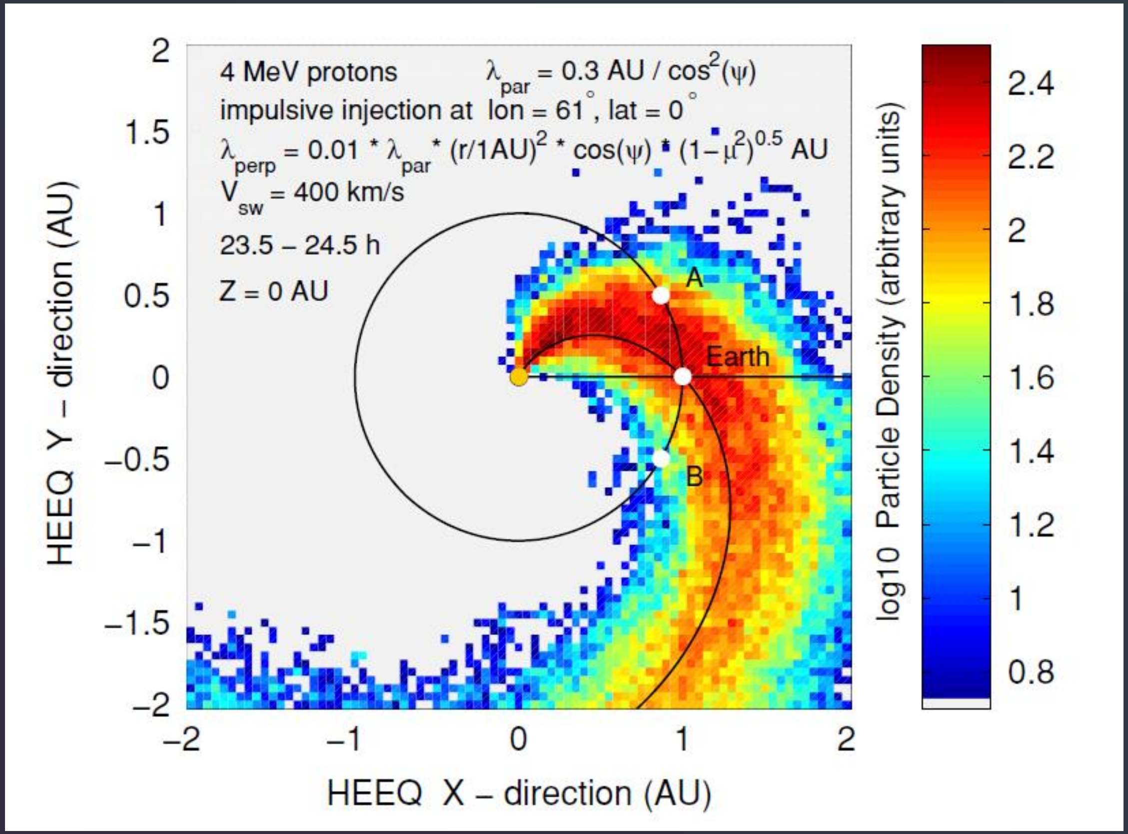
- 1D approach: assumes that particles are tied to field lines – no propagation across the field



Kallenrode, 1993

3D transport models

- 3D models including perpendicular transport (Zhang et al 2009, Dröge et al 2011). Requires $\lambda_{\|}$, $\lambda_{\perp}$



Dröge et al 2011

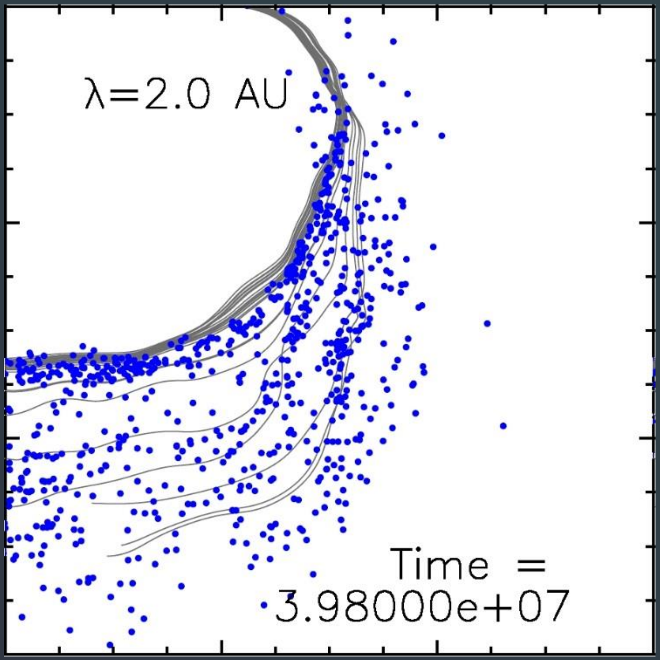
3D full orbit propagation code

- Integrate test particle trajectories in specified magnetic and electric fields (Dalla et al 2005, Marsh et al 2013)

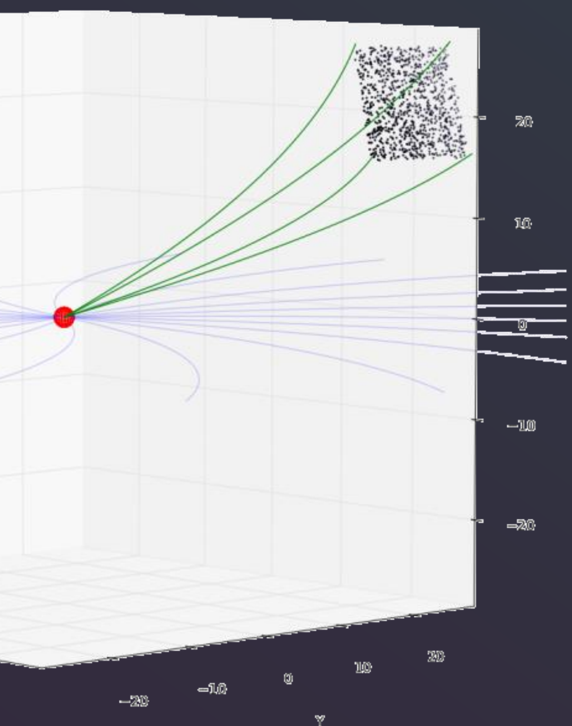
- Effect of small scale turbulence implemented as 'ad-hoc scattering' according to mean free path λ

$$\frac{d\mathbf{x}}{dt} = \frac{\mathbf{p}}{m\gamma}$$

$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E} + \frac{1}{c}\frac{\mathbf{p}}{m\gamma} \times \mathbf{B}\right)$$

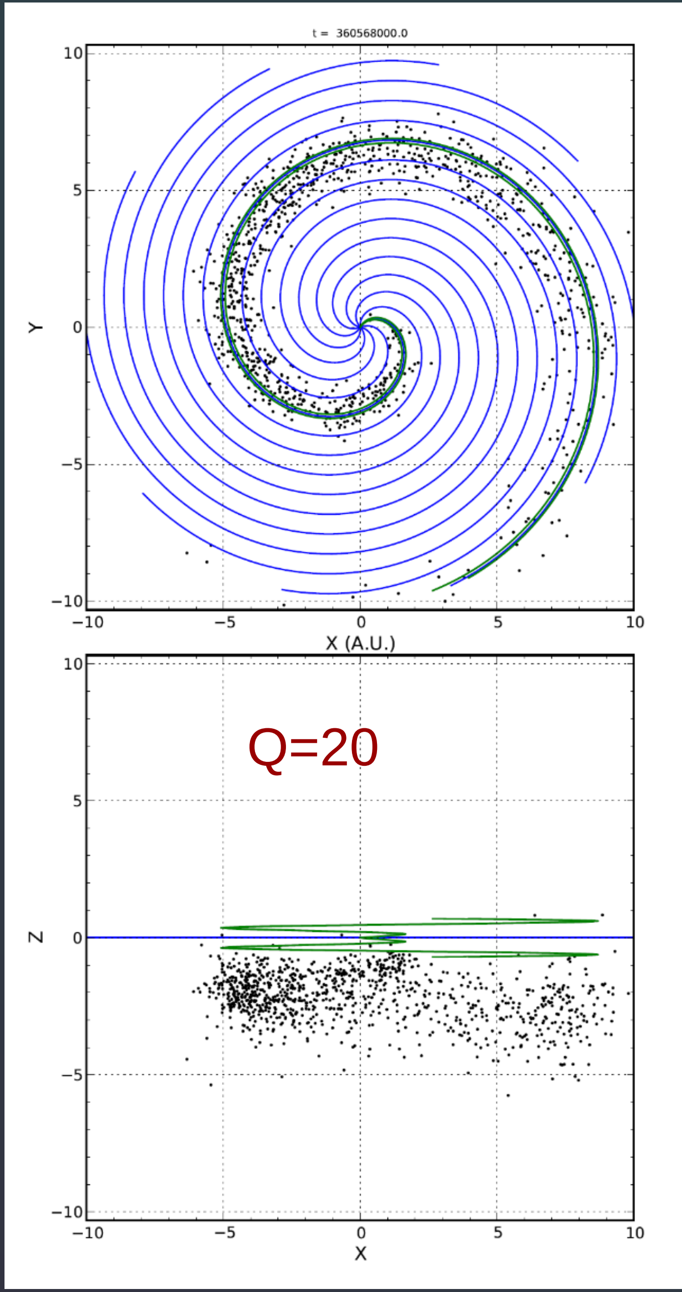


Guiding centre drifts

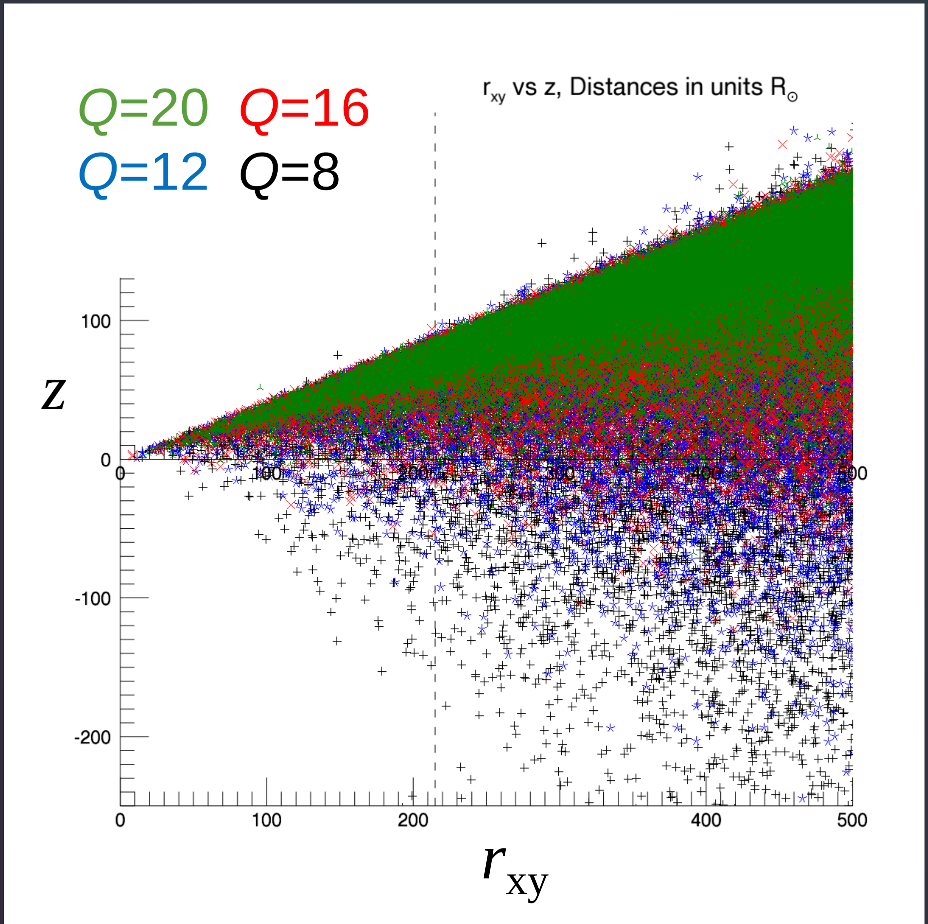


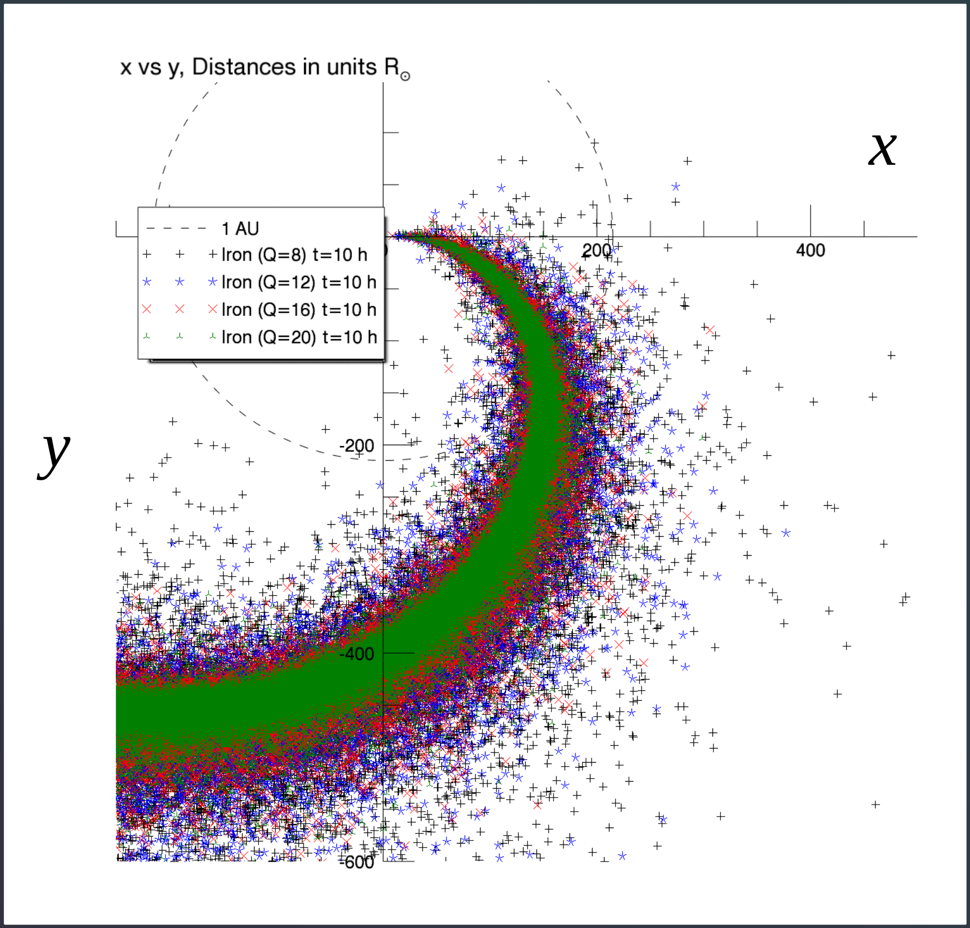
- Due to curvature and gradient of Parker spiral [Dalla et al 2013]
- Fe at 100 Mev/nuc
- t=100 hrs

Marsh et al, 2013

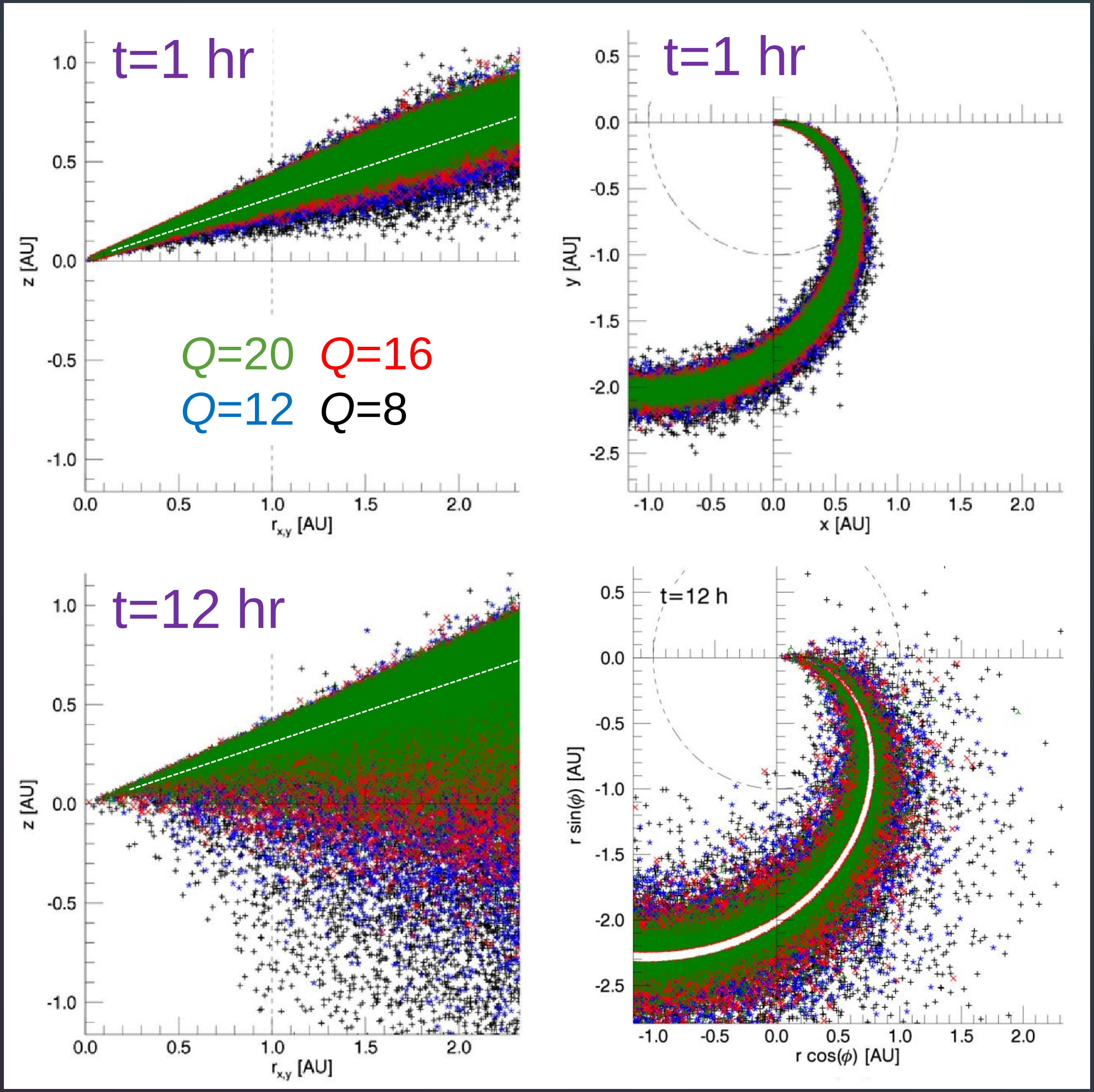


Fe propagation



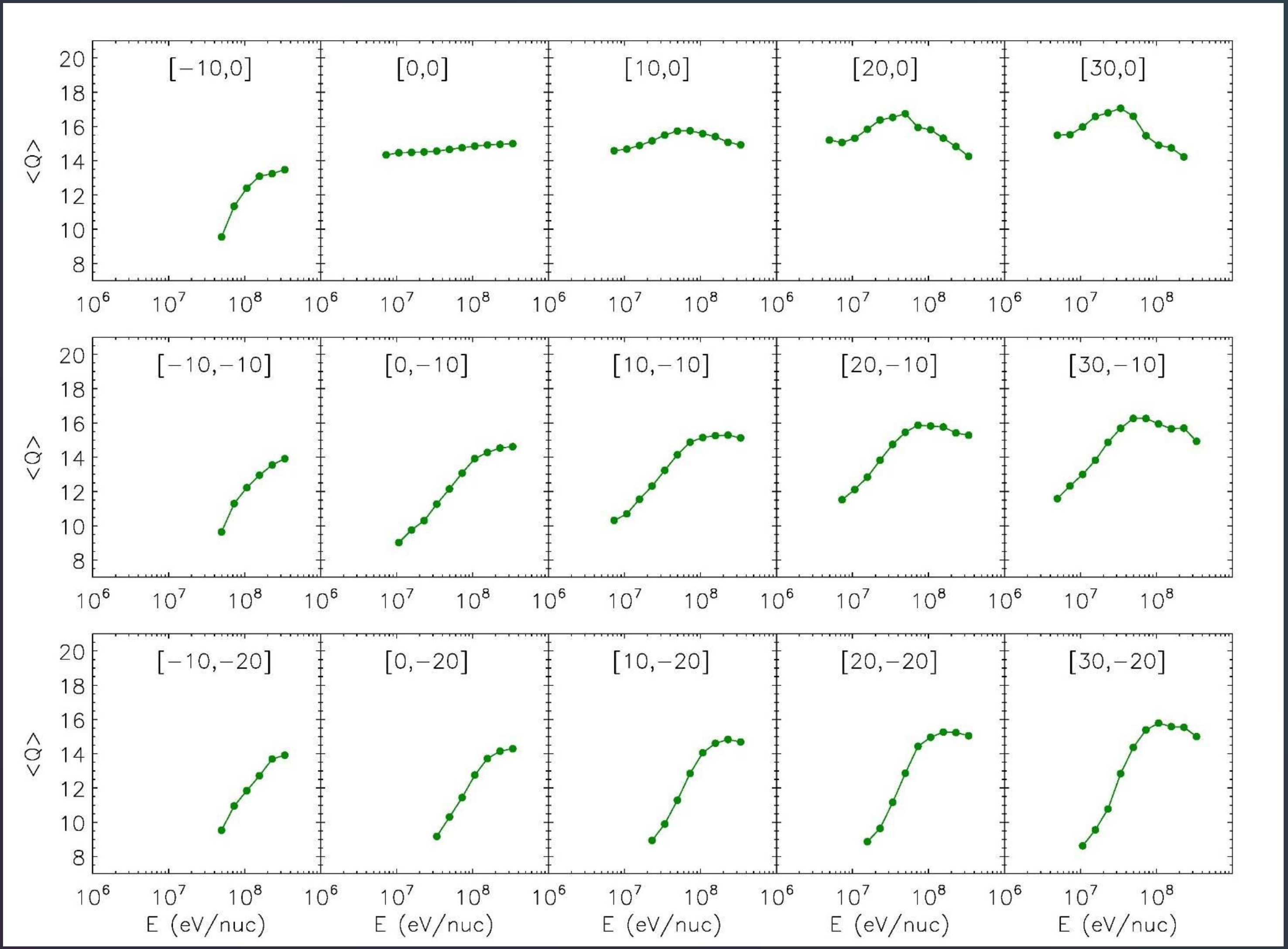


Fe
SEP
ions



t=1 hr
t=1 hr
Q=20 Q=16
Q=12 Q=8
z [AU]
$r_{x,y}$ [AU]
y [AU]
x [AU]
t=12 hr
t=12 h
z [AU]
$r_{x,y}$ [AU]
r sin(φ) [AU]
r cos(φ) [AU]

1 AU energy distribution of Q



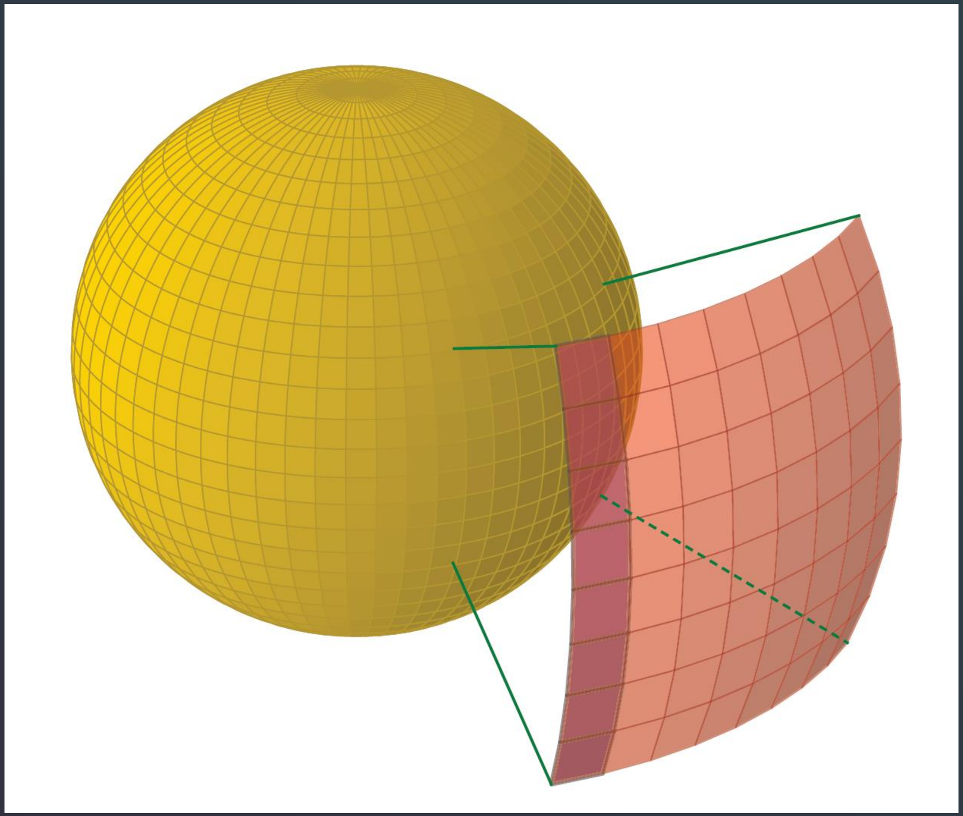
Dalla et al, ApJ 2017

Shock-like injection region

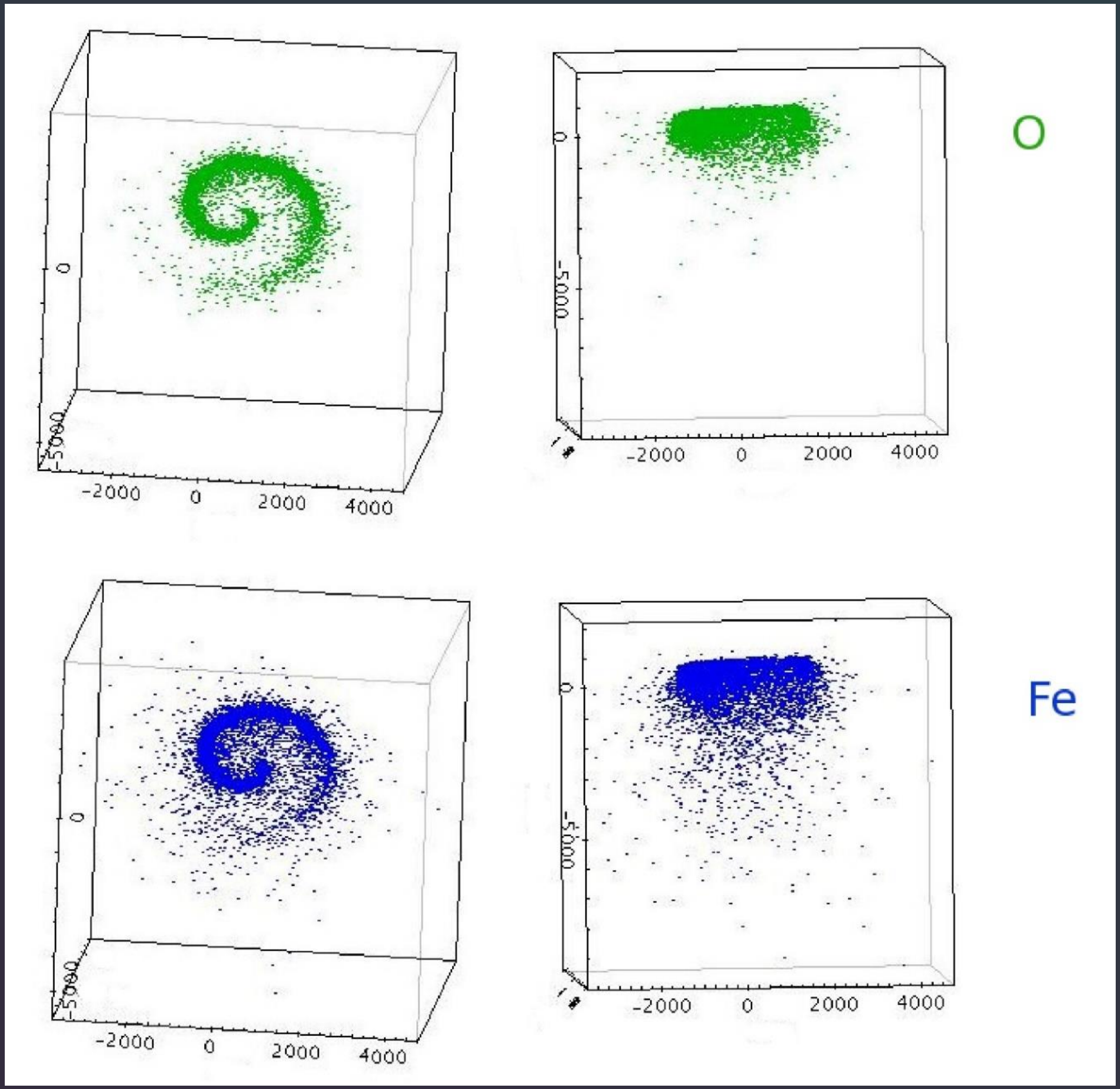
- Effect of variation of SEP acceleration efficiency along shock front

- Latitude dependence of drift velocity

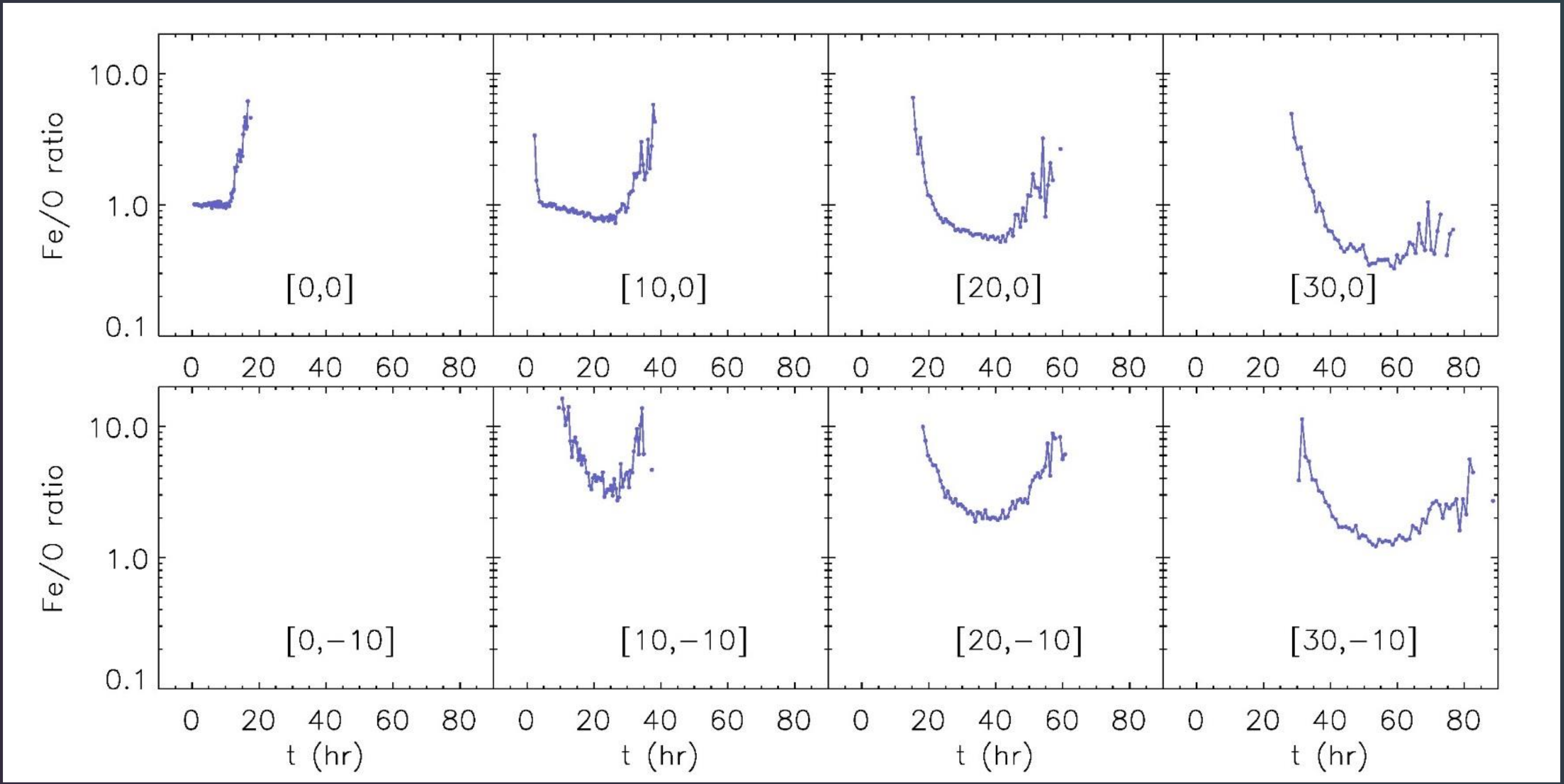
- Overall 3D propagation will 'process' the injection properties



Transport of Fe and O ions



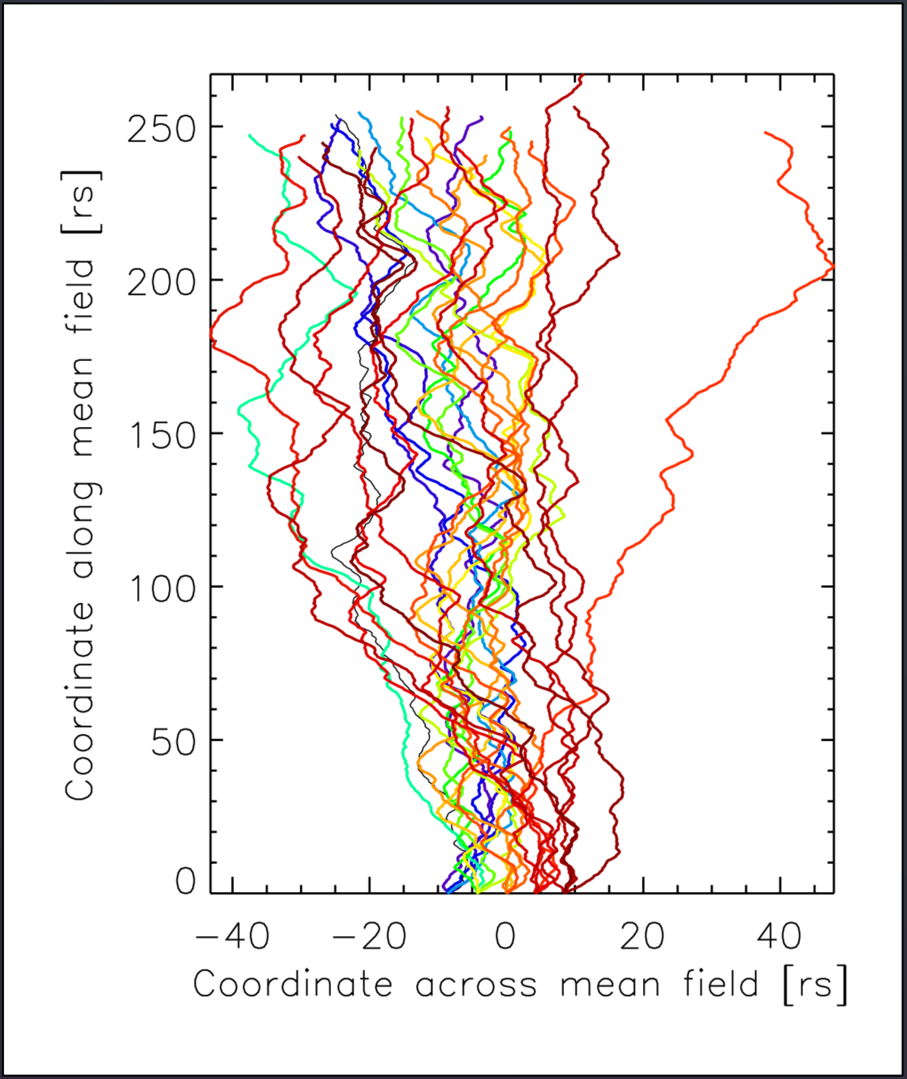
Fe/O ratio



Fe and O at 10-30 MeV/nuc

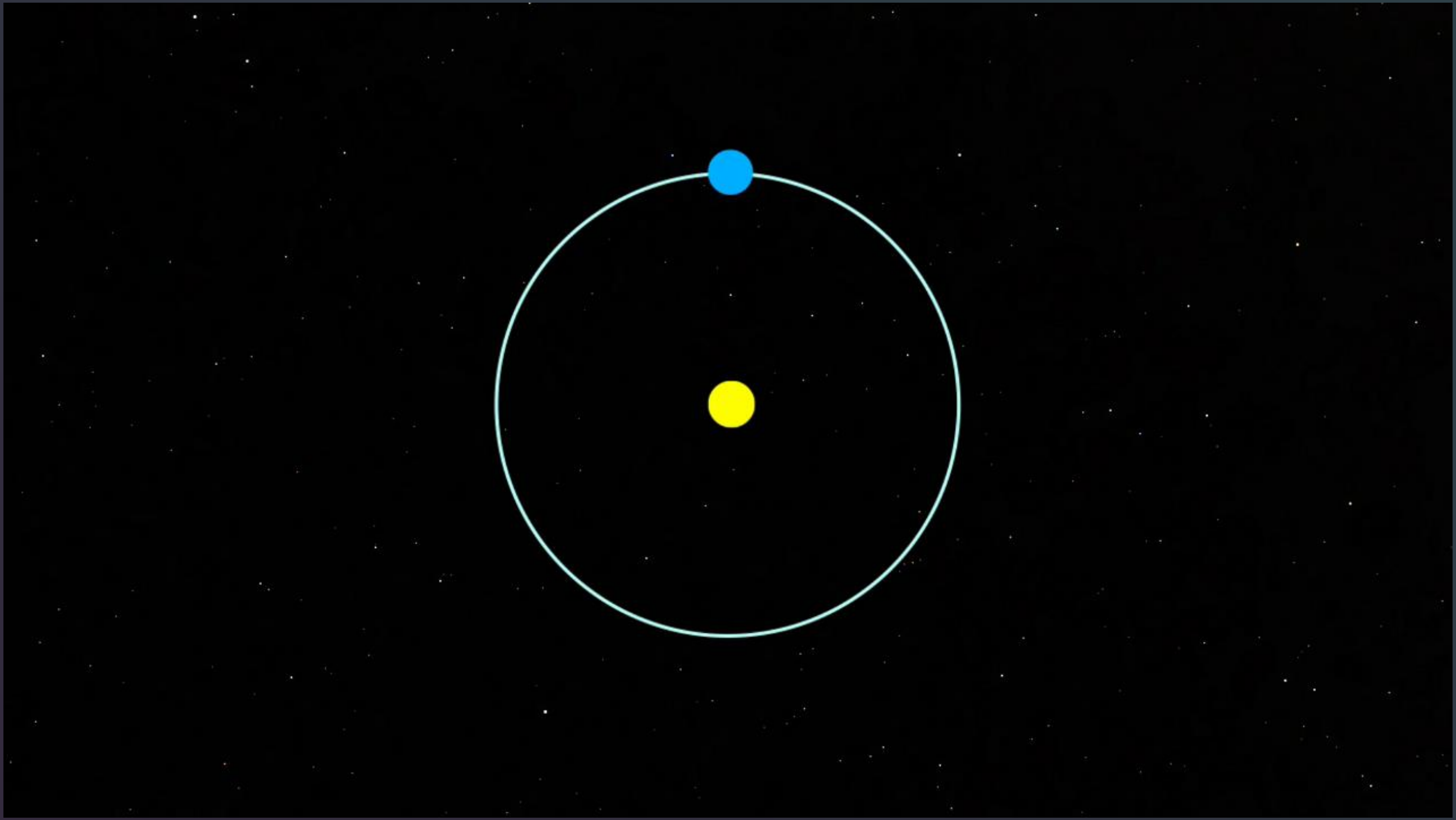
Dalla et al, A&A 2017

Magnetic field line meandering

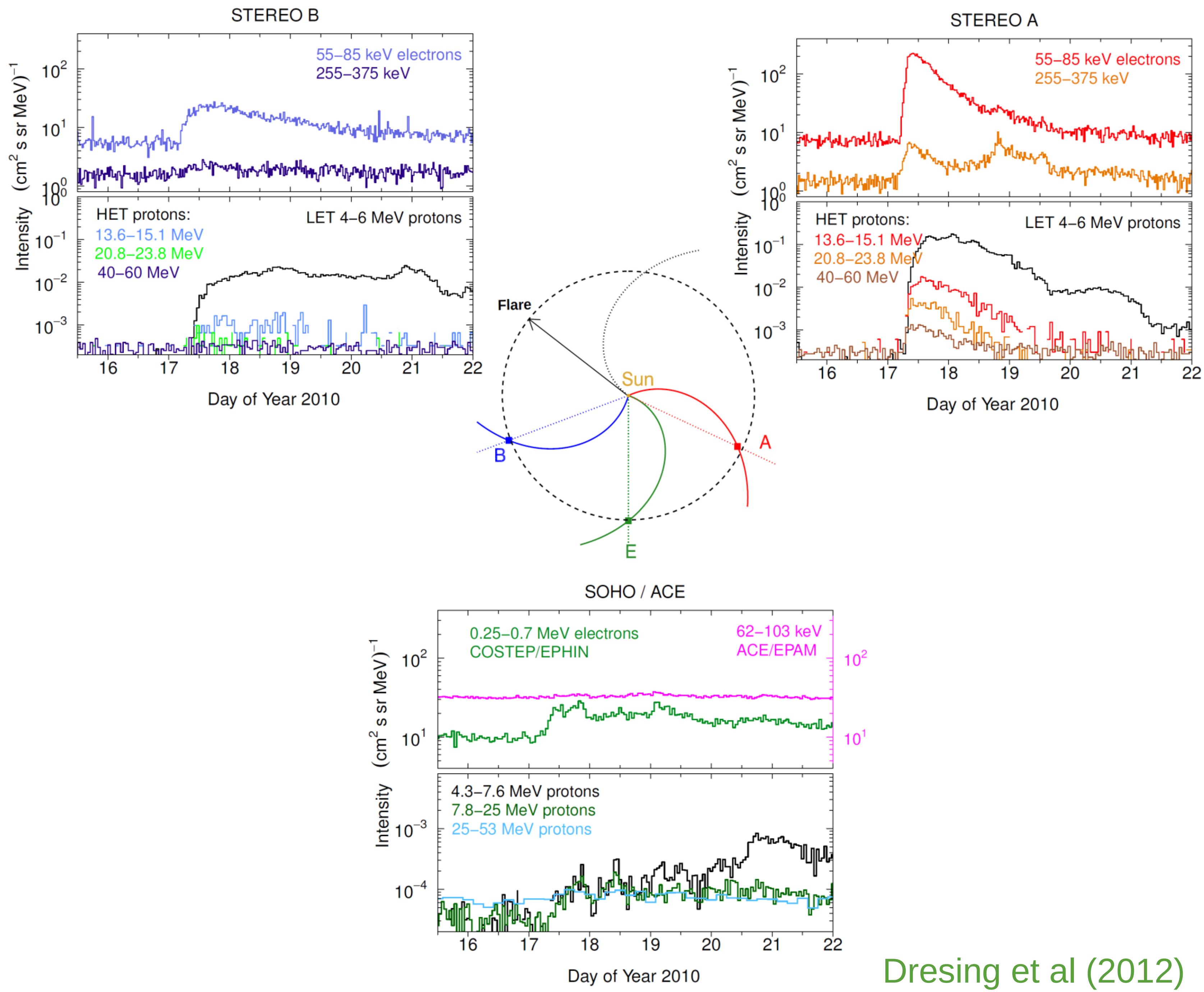


- Turbulence produces meandering in the magnetic field lines
- Contribution to particle transport across the mean field

Magnetic field line meandering



Laitinen et al, 2016

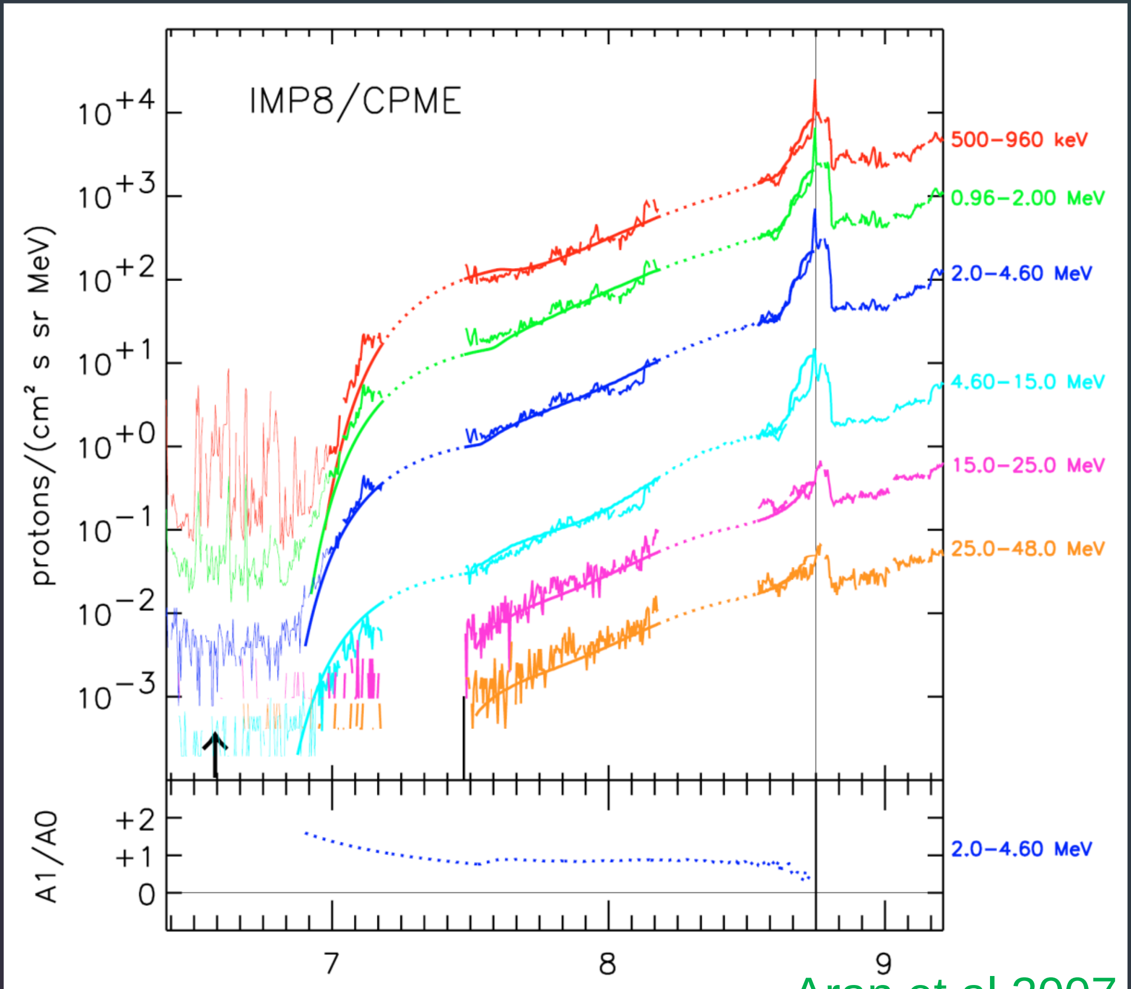


Dresing et al (2012)

Approaches to modelling for Space Weather

SOLPENCO

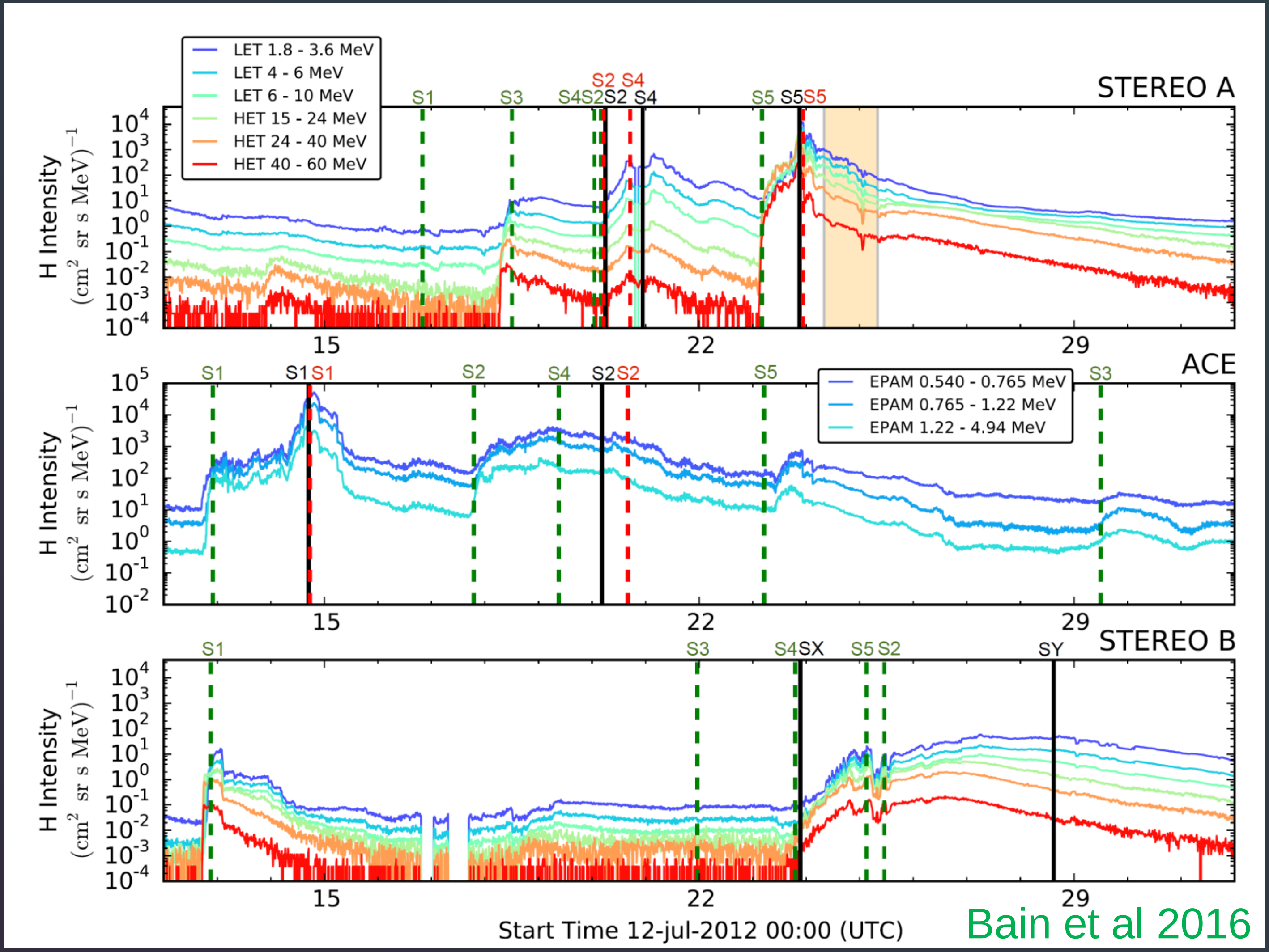
- 1D focussed transport propagation coupled with MHD shock modelling (Aran et al 2005)



Aran et al 2007

ENLIL + SEP propagator

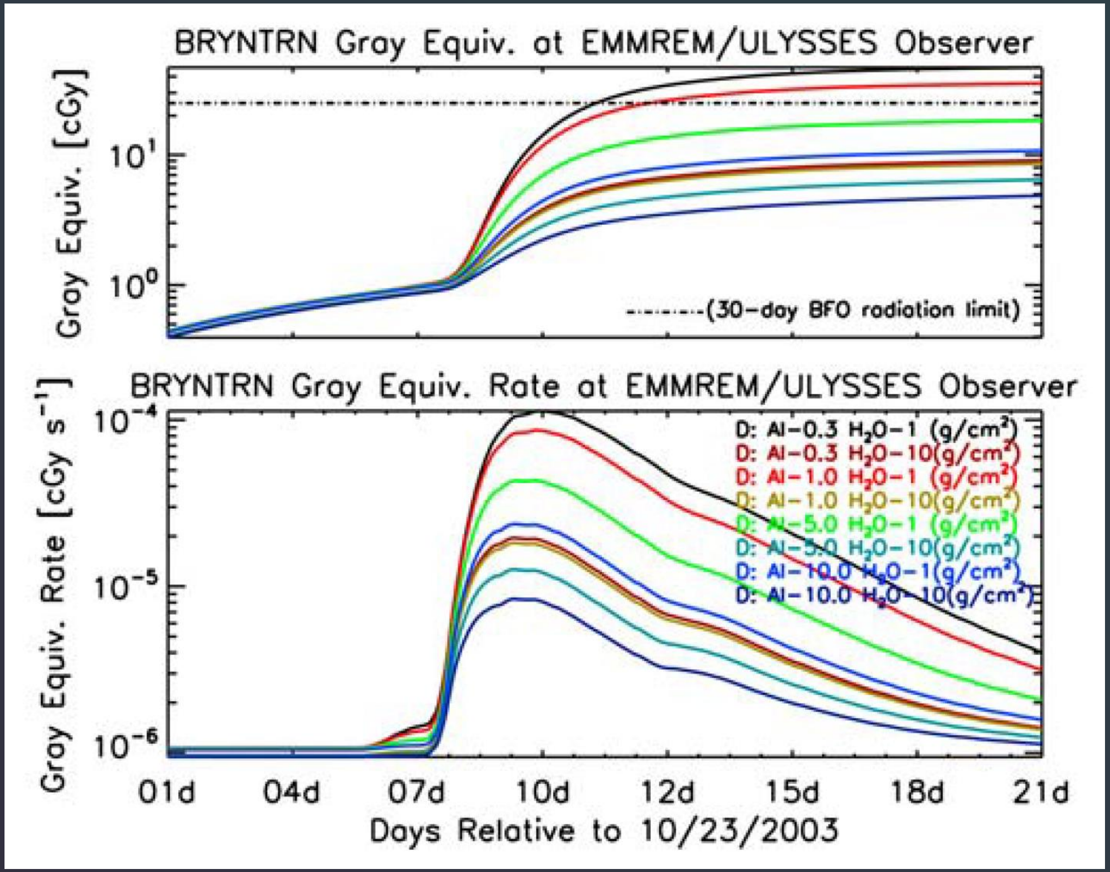
- ENLIL used to determine shock locations and connection to observer - coupled 1D scatter free particle motion (Luhmann et al, 2010, Bain et al 2016)



Bain et al 2016

EPREM/EMMREM

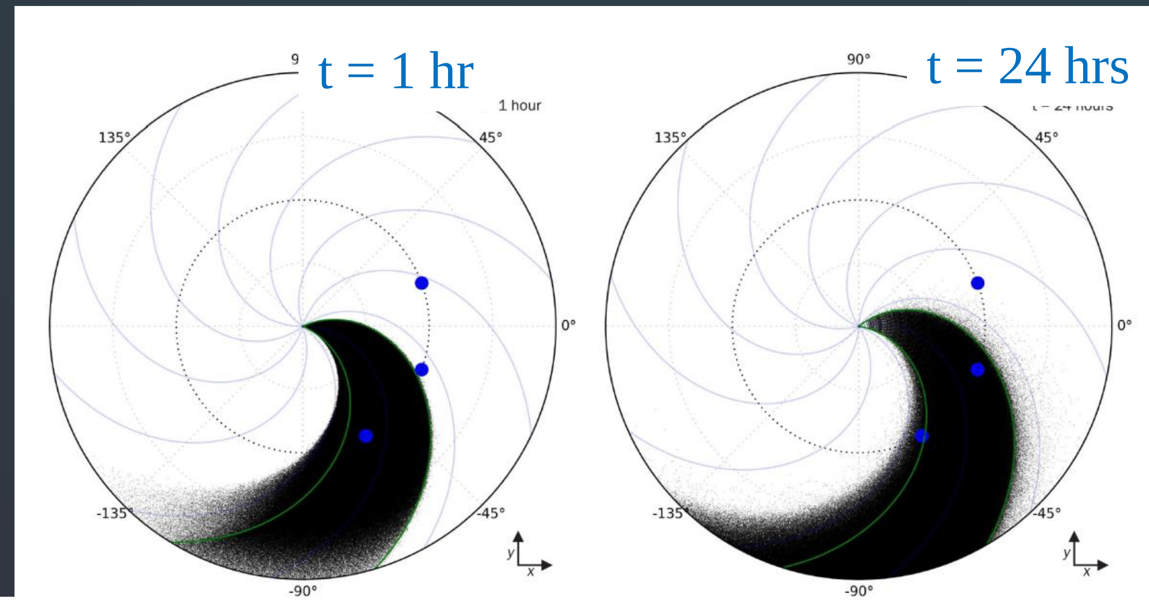
- EPREM couples 1D focussed transport equation with convection-diffusion equation to describe transport in 3D (Schwadron et al 2010)
- EPREM + MHD CME shock simulation in solar corona (Kozarev et al 2013)

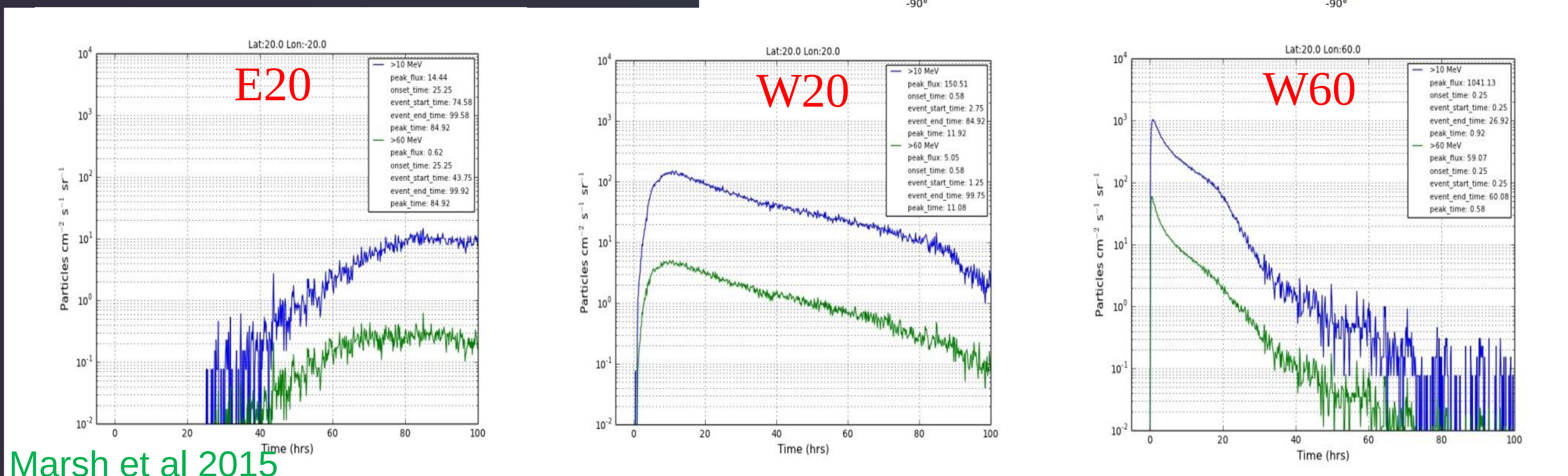


Schwadron et al, 2010

SPARX

- Based on 3D test particle propagation (Marsh et al 2015)





Summary

- Many advances and significant challenges in understanding SEP acceleration and propagation
- Simulations show that due to gradient and curvature drifts, and to magnetic field line meandering, a 3D description is needed for SEP propagation
- 3D drift-associated propagation qualitatively reproduces two key heavy ion observations: energy dependence of <*Q*> and time dependence of Fe/O ratio
- A number of Space Weather models for SEP forecasting are now available