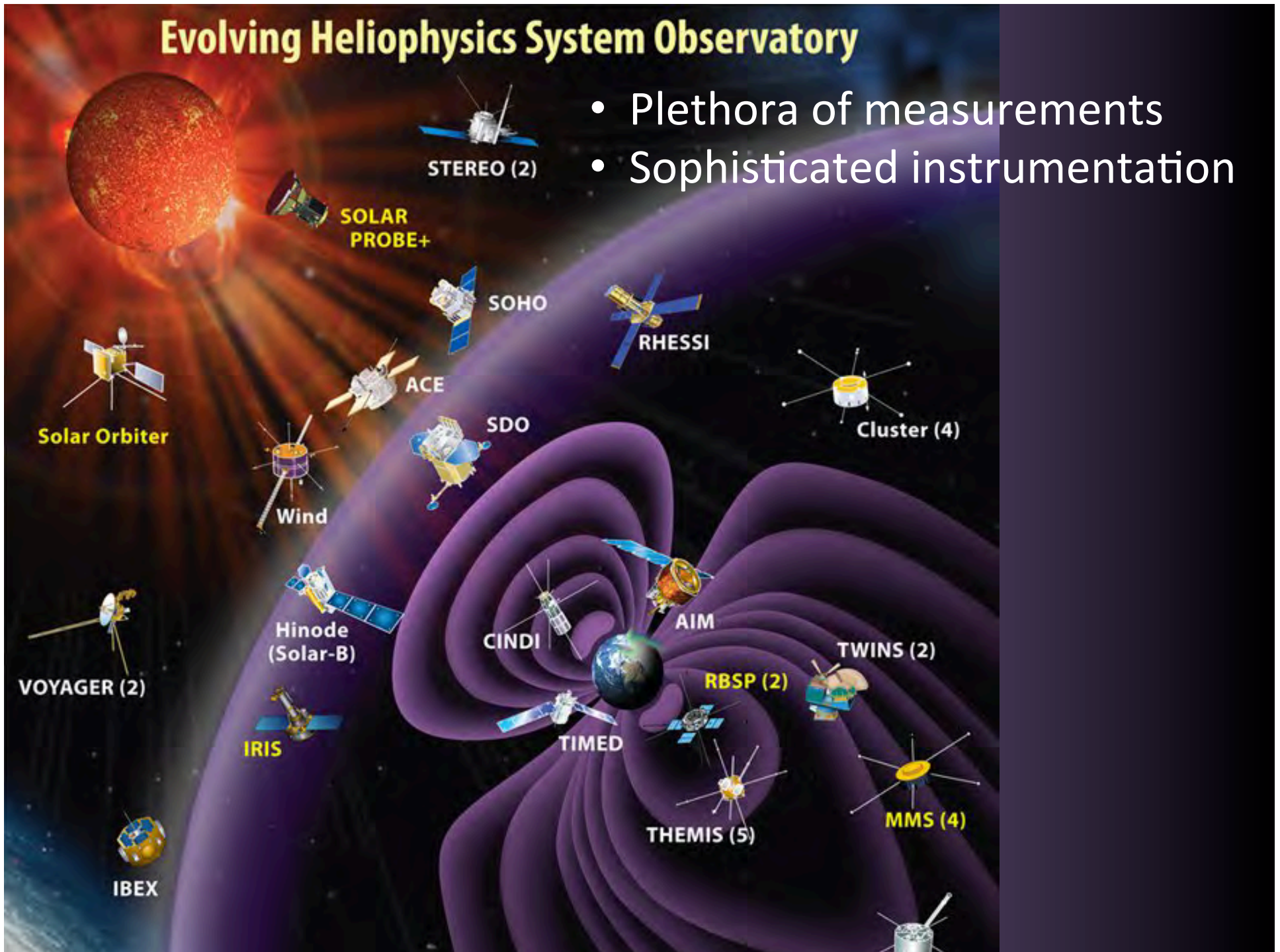# Solar Energetic Particles: Origin, Acceleration and Transport
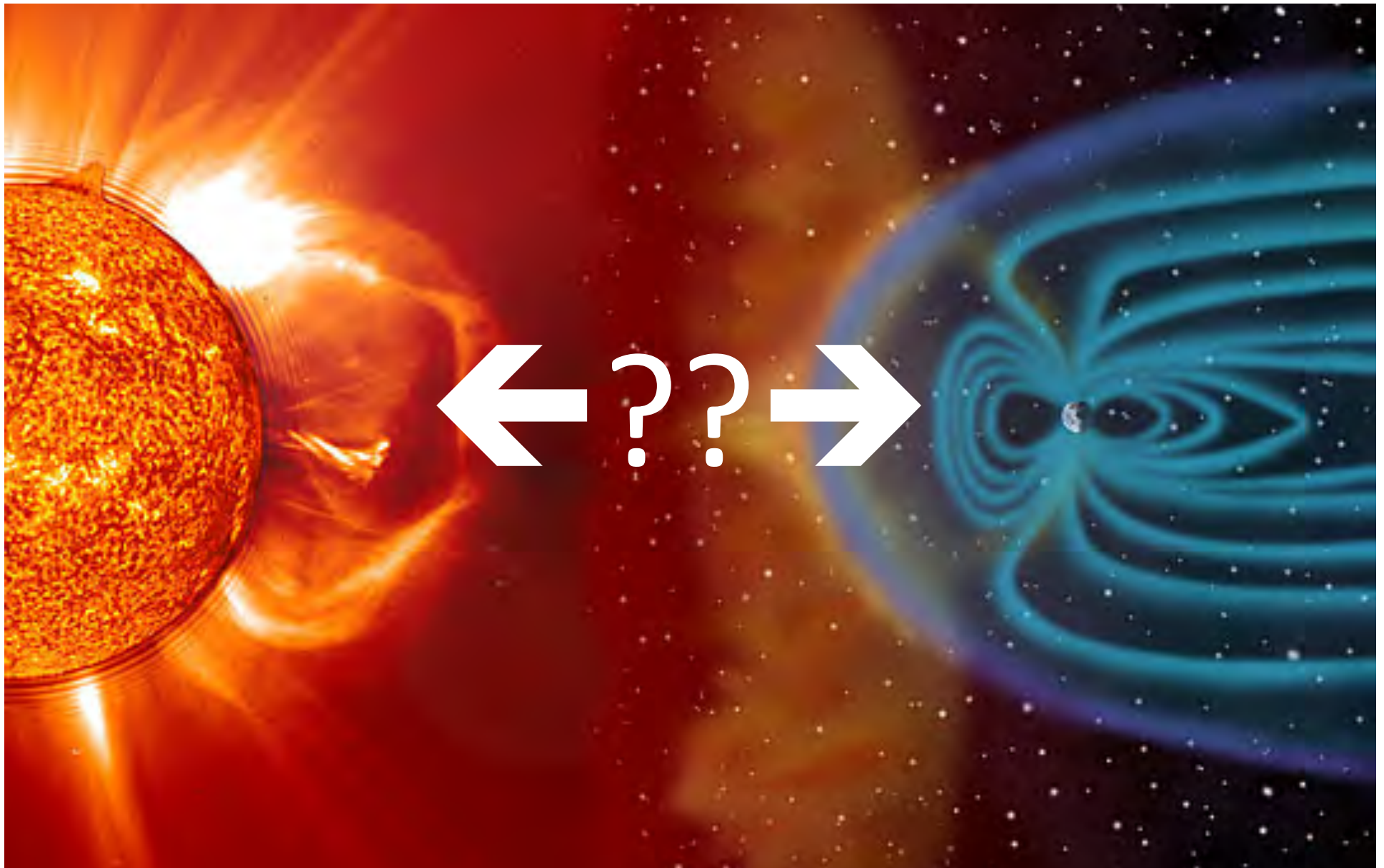
Christina M.S. Cohen

Caltech

Evolving Heliophysics System Observatory

- Plethora of measurements
- Sophisticated instrumentation

STEREO (2)

SOLAR PROBE+

SOHO

RHESSI

ACE

SDO

Cluster (4)

Solar Orbiter

Wind

Hinode (Solar-B)

CINDI
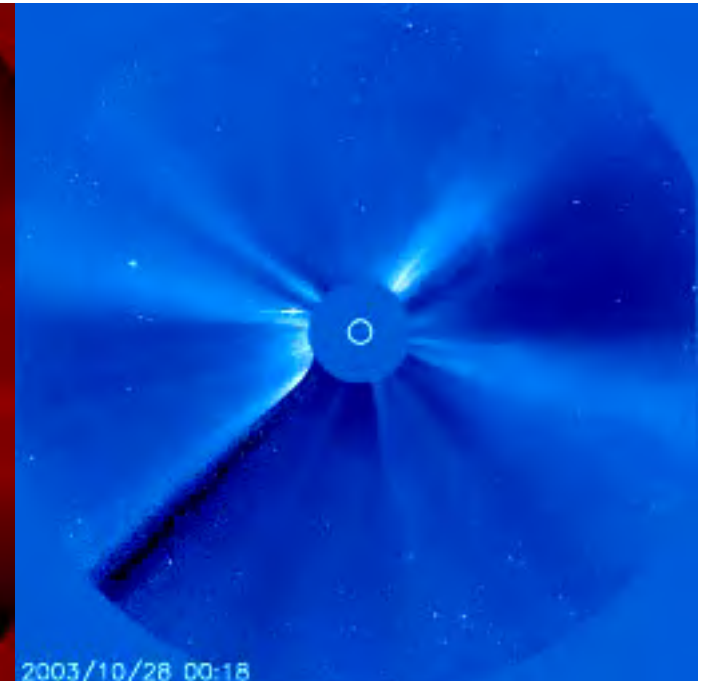
AIM

TWINS (2)

VOYAGER (2)

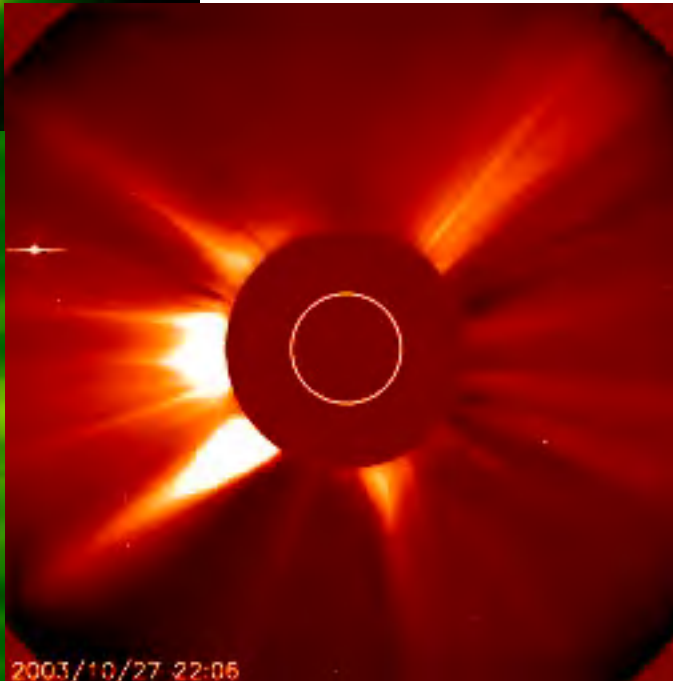RBSP (2)
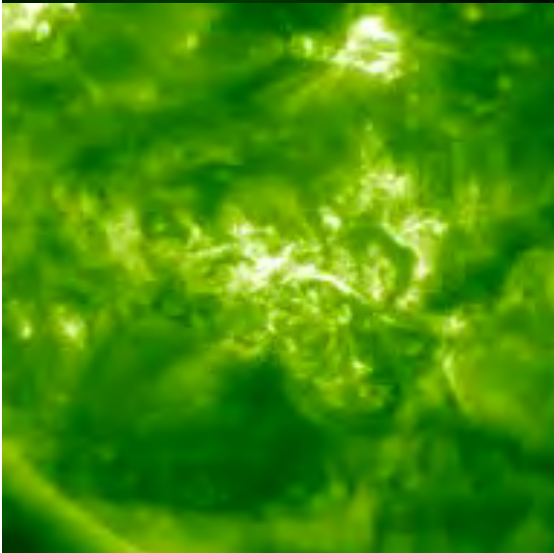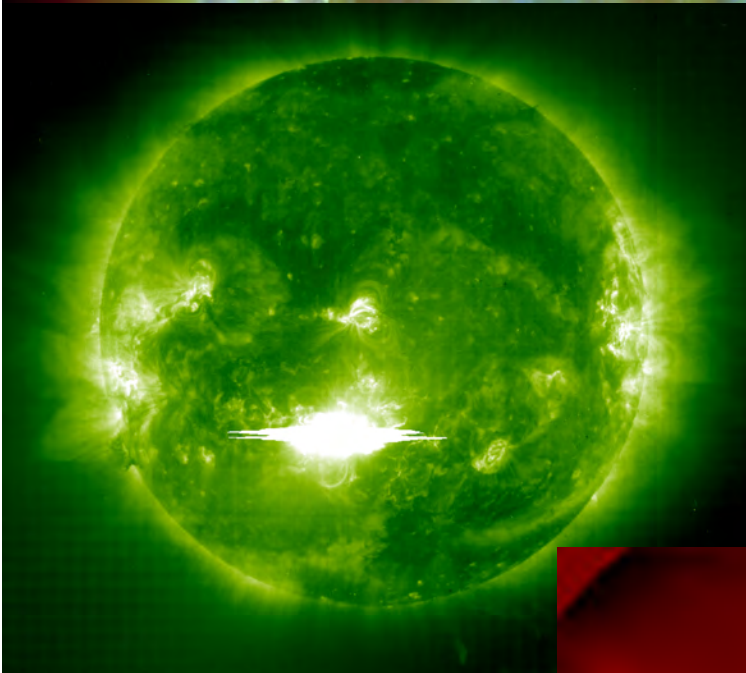
IRIS

TIMED

MMS (4)

THEMIS (5)

IBEX

Lots of Space in Space

Lots of Space in Space
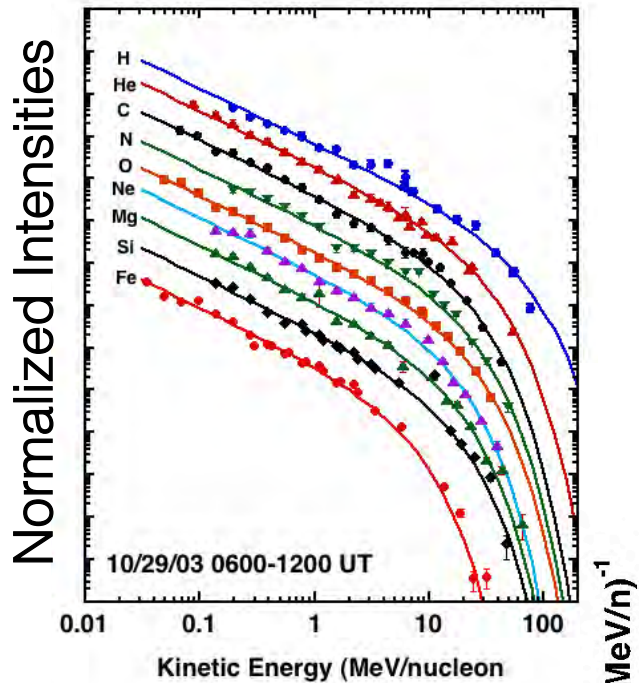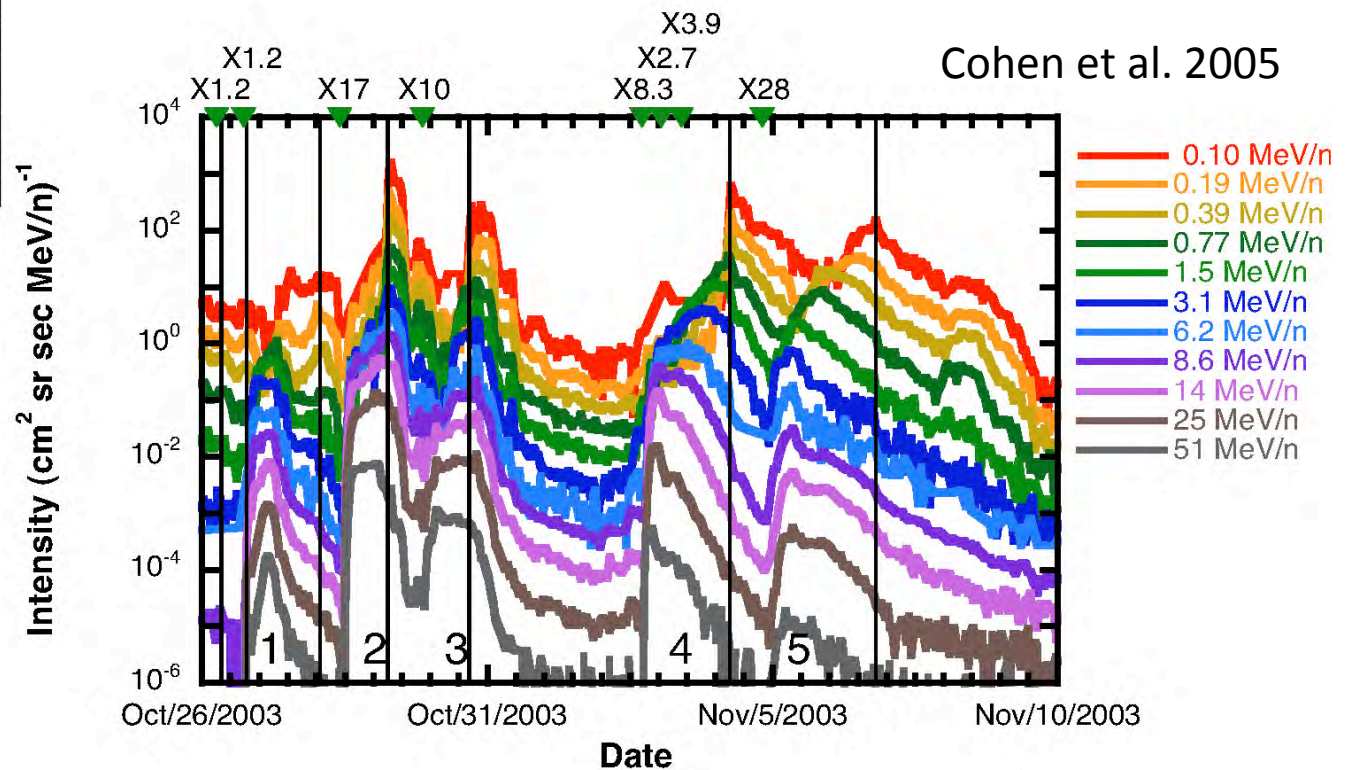
- How do we connect this...

Lots of Space in Space

· How do we connect this...

... to this?
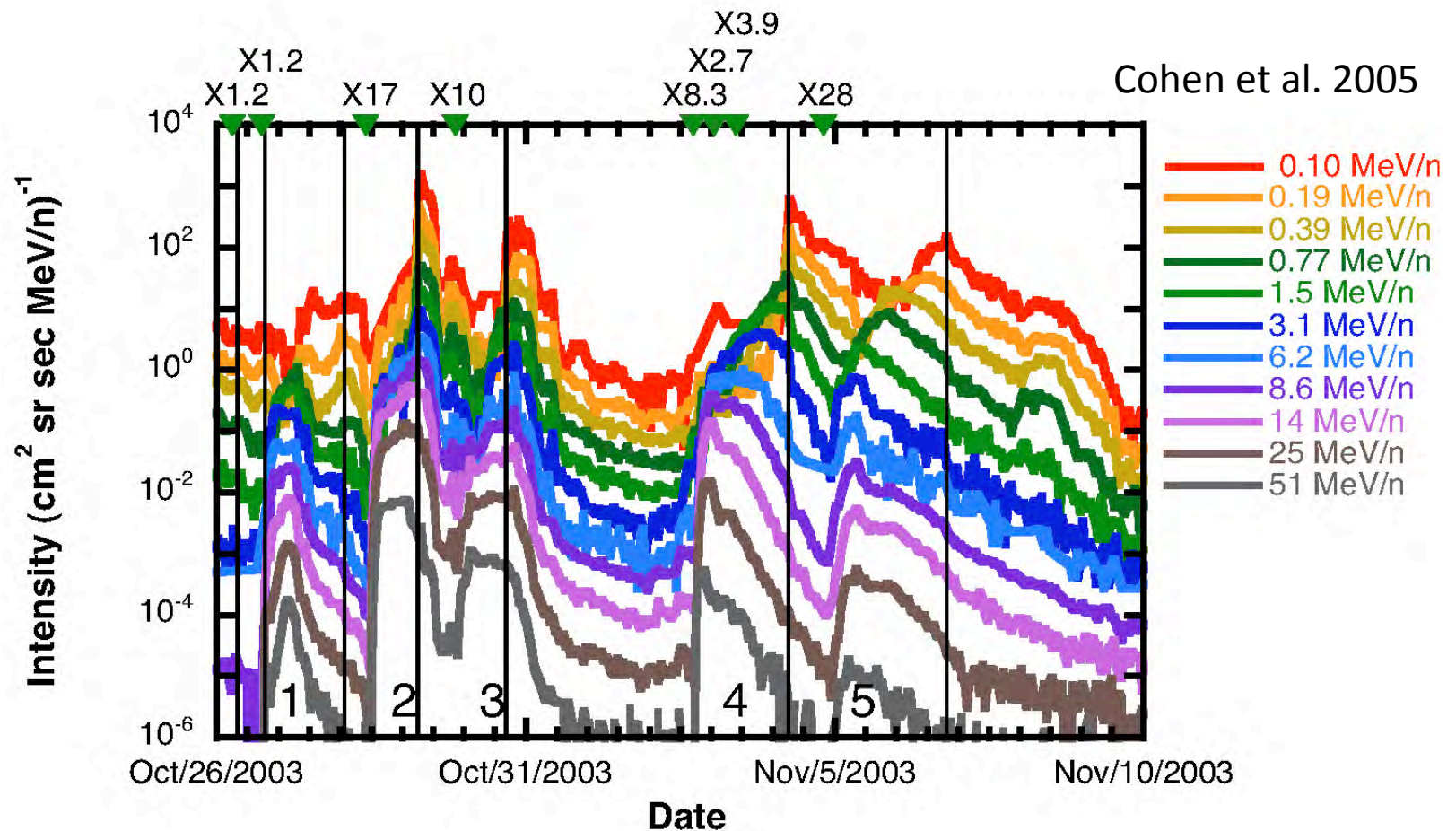
Normalized Intensities

10/29/03 0600-1200 UT

Kinetic Energy (MeV/nucleon)

Mewaldt et al. 2005

Cohen et al. 2005

Lots of Space in Space

- SEP events are extremely variable
  - Time profiles

Cohen et al. 2005

Lots of Space in Space

- SEP events are extremely variable
  - Time profiles
  - Spectra

Oxygen Fluences
ACE/SIS

Legend:
- 1/23/12
- 1/27/12
- 3/7/12
- 3/13/12
- 5/17/12
- 5/15/13
- 5/22/13
- 9/30/13
- 1/7/14
- 2/25/14
- 7/14/00
- 11/8/00
- 9/24/01
- 11/4/01
- 11/22/01
- Sum 5 Cycle 23
- Sum 10 Cycle 24

Mewaldt et al. 2017

Oxygen/cm^2 vs Kinetic Energy (MeV/nuc)

Lots of Space in Space

- SEP events are extremely variable
  - Time profiles
  - Spectra
  - Composition
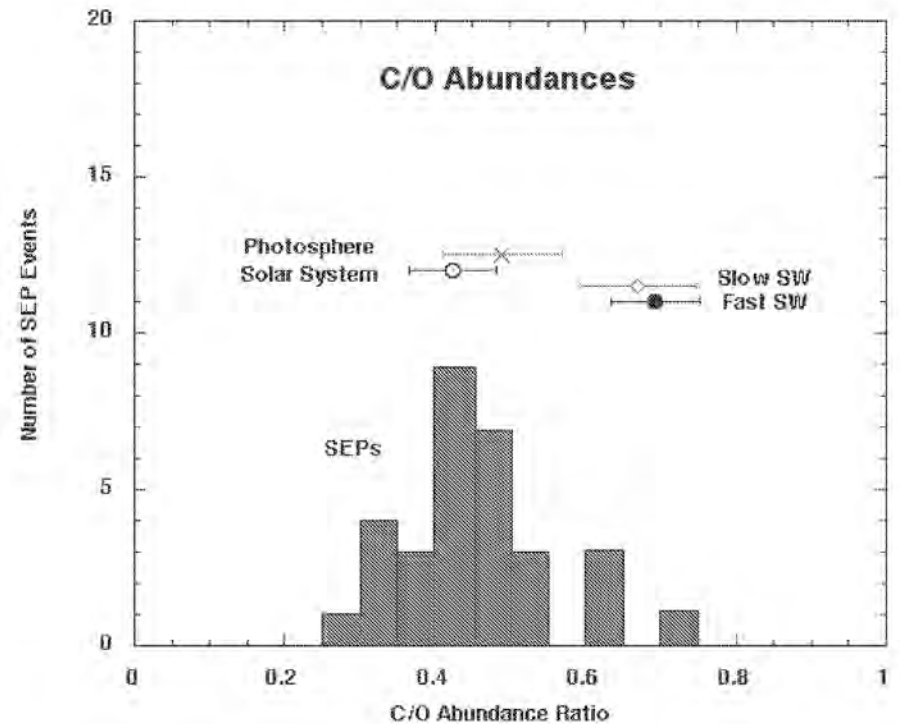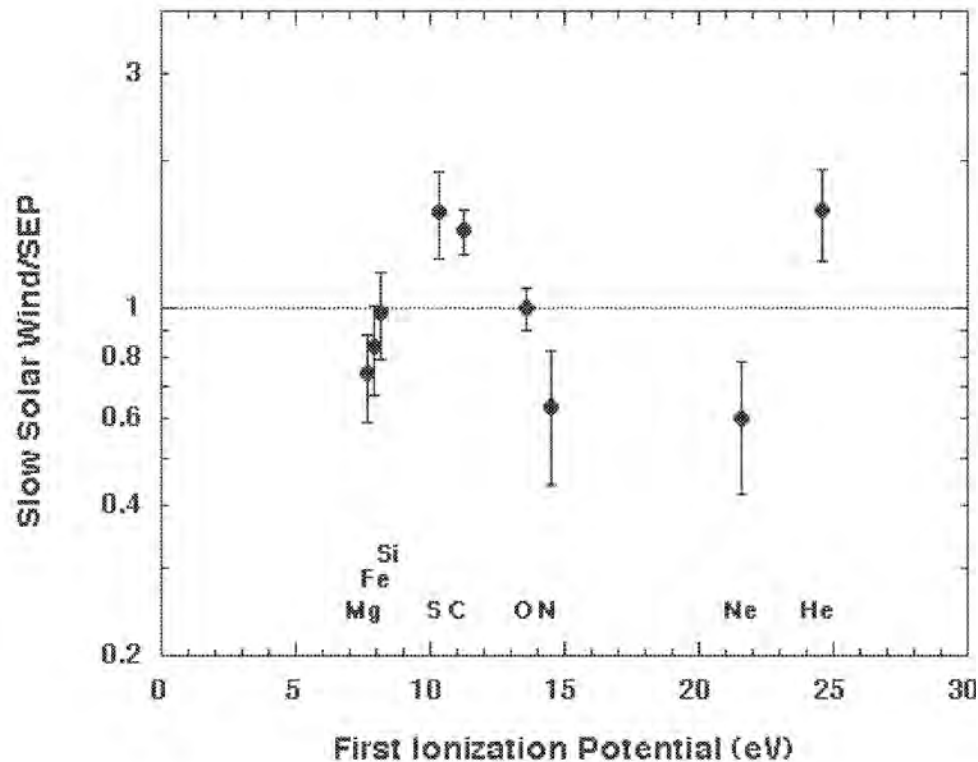

Fe/O at 12-33 MeV/n
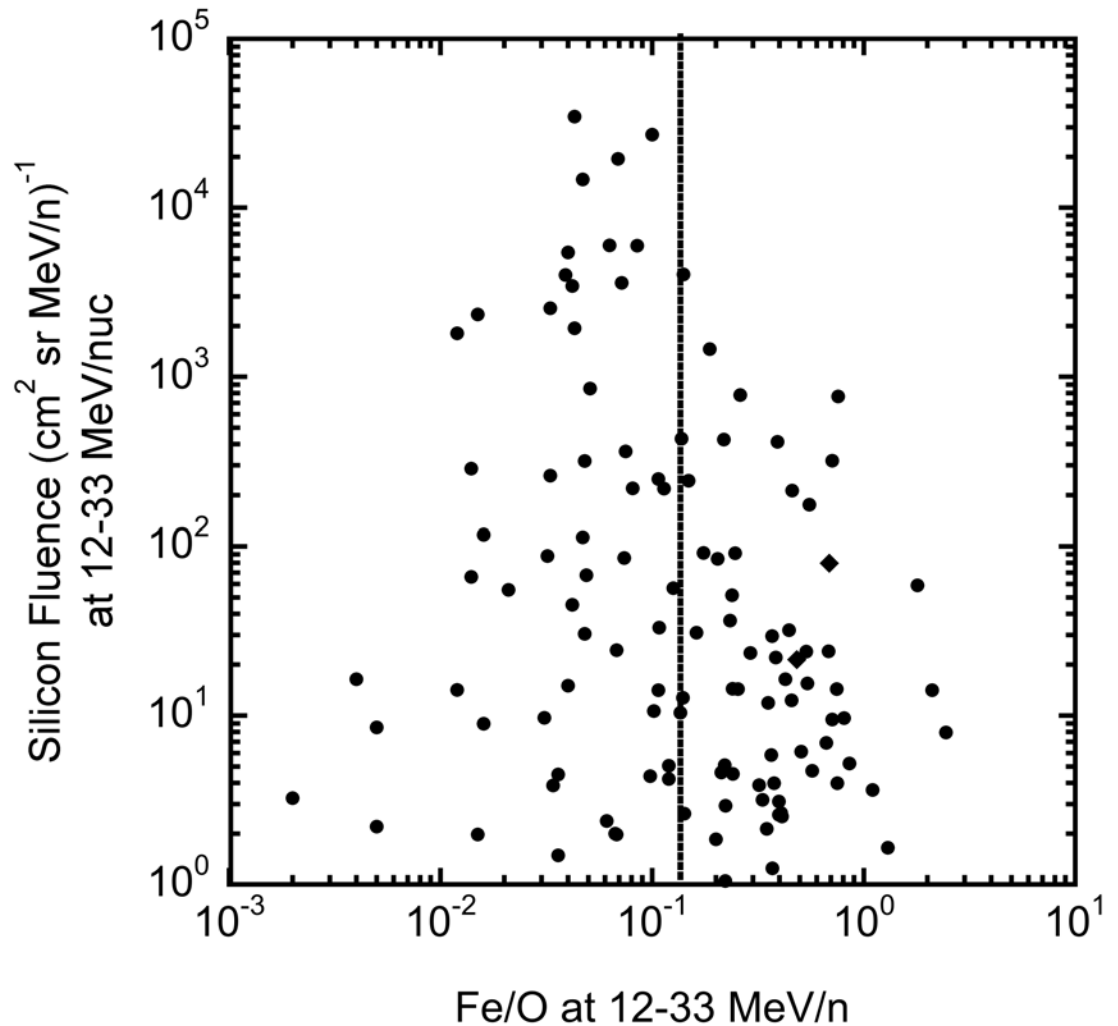
Lots of Space in Space

- SEP events are extremely variable
  - Time profiles
  - Spectra
  - Composition
- All the characteristics are impacted by
  - Origin
  - Acceleration
  - Transport
- We've learned a lot but there *remains a lot to learn*
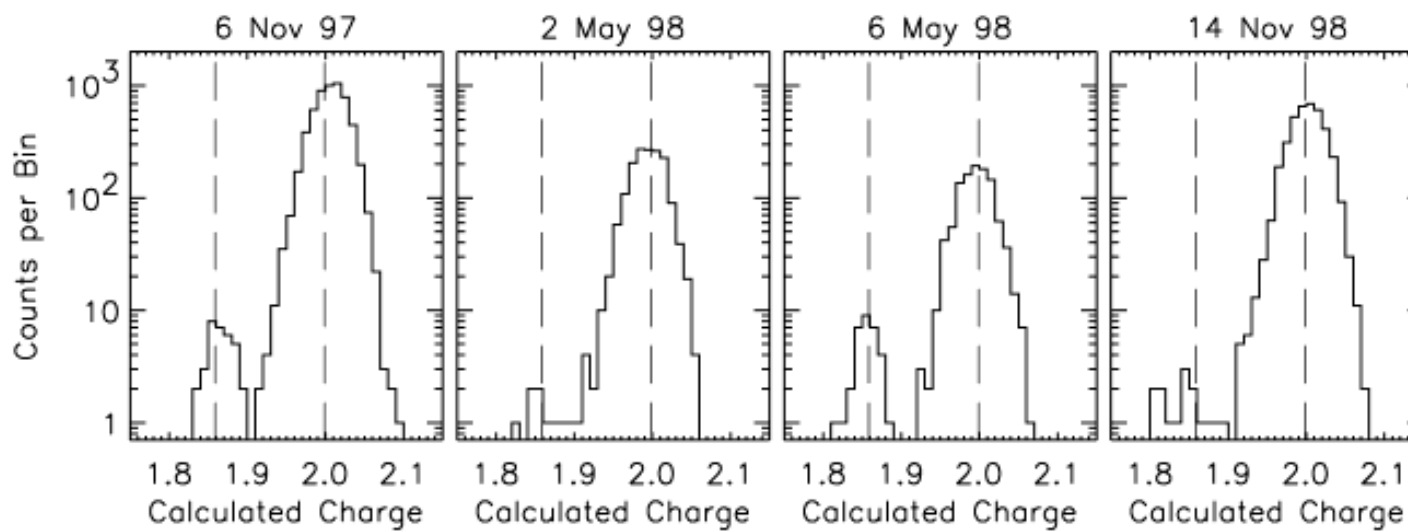
Origin

- Solar Wind & SEP have different composition

Mewaldt et al. 2001

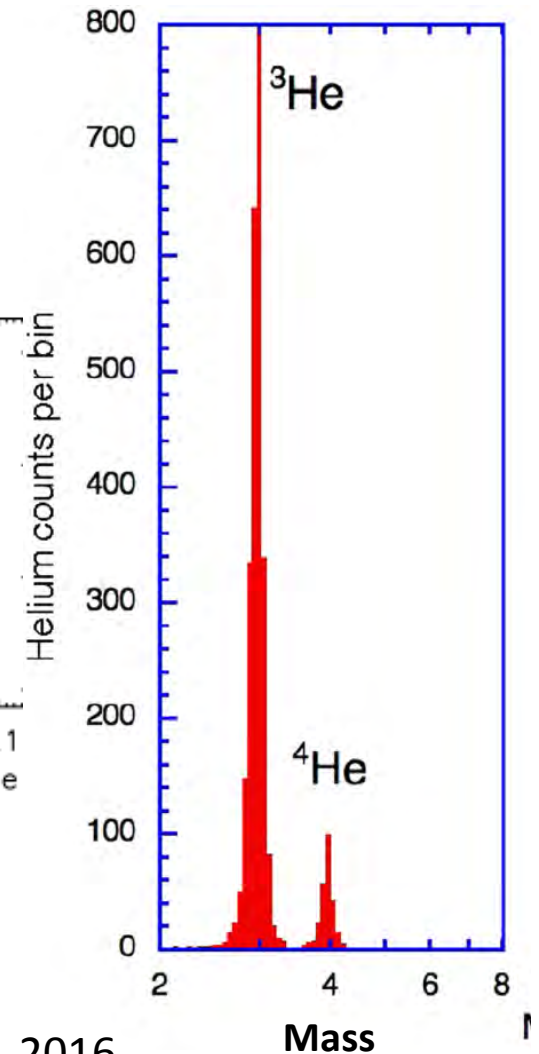# Origin

- Solar Wind & SEP have different composition
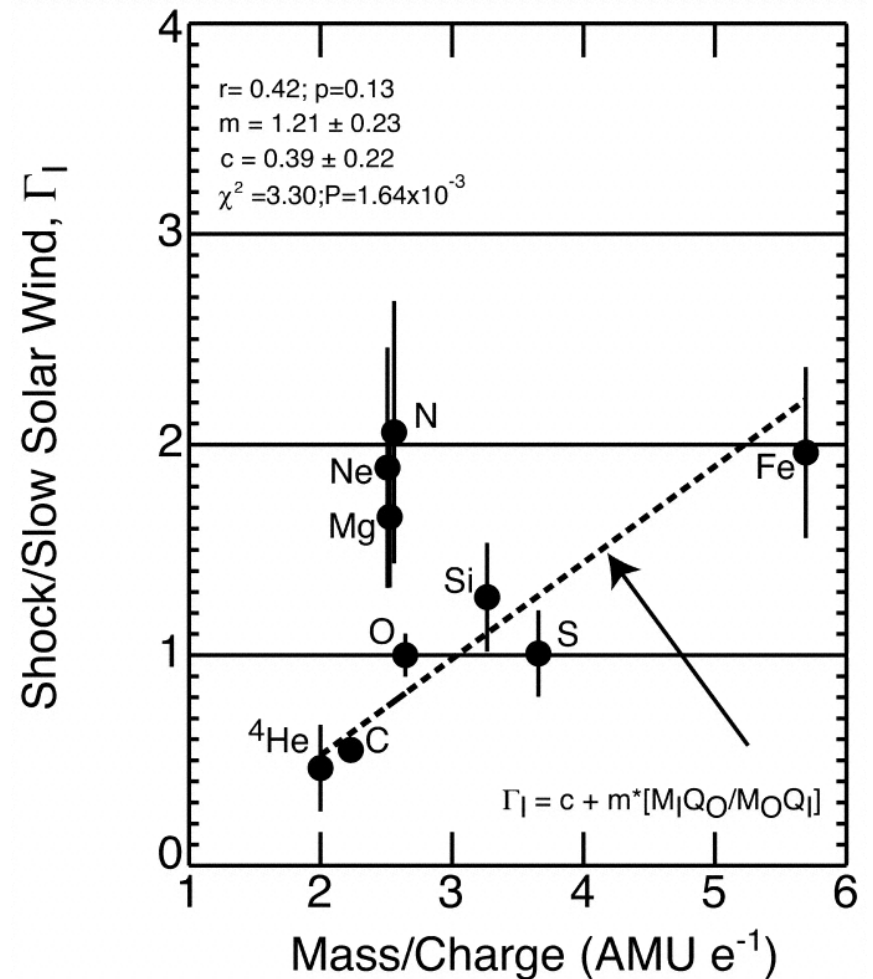 - ^{3}He/^{4}He especially (SW~ 5×10^{-4})

Wiedenbeck et al. 1999

Mason et al. 2016

Origin

- Solar Wind & SEP have different composition
  - $^3He/^4He$ especially (SW~ 5×10^{-4})

Desai et al. 2003

Origin
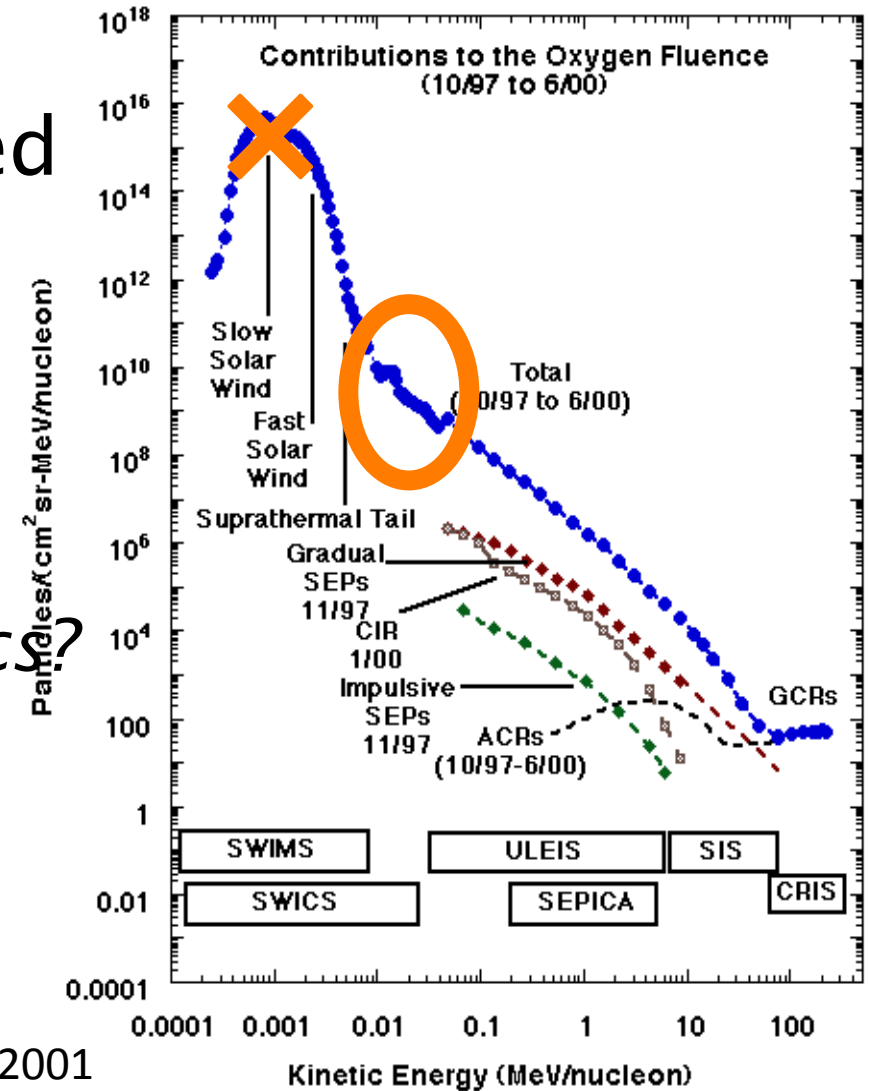
- Solar Wind & SEP have different composition
  - ^{3}He/^{4}He especially (SW~ 5x10^{-4})
- SEPs systematically related to upstream material

Desai et al. 2003

$$\log(\Gamma_I) = c + m^*[M_I Q_O / M_O Q_I]$$

r = -0.92; p=7.9x10^{-5}
m = -0.62 ± 0.06
c = 0.59 ± 0.06
χ^2_ν =1.89;P=0.06
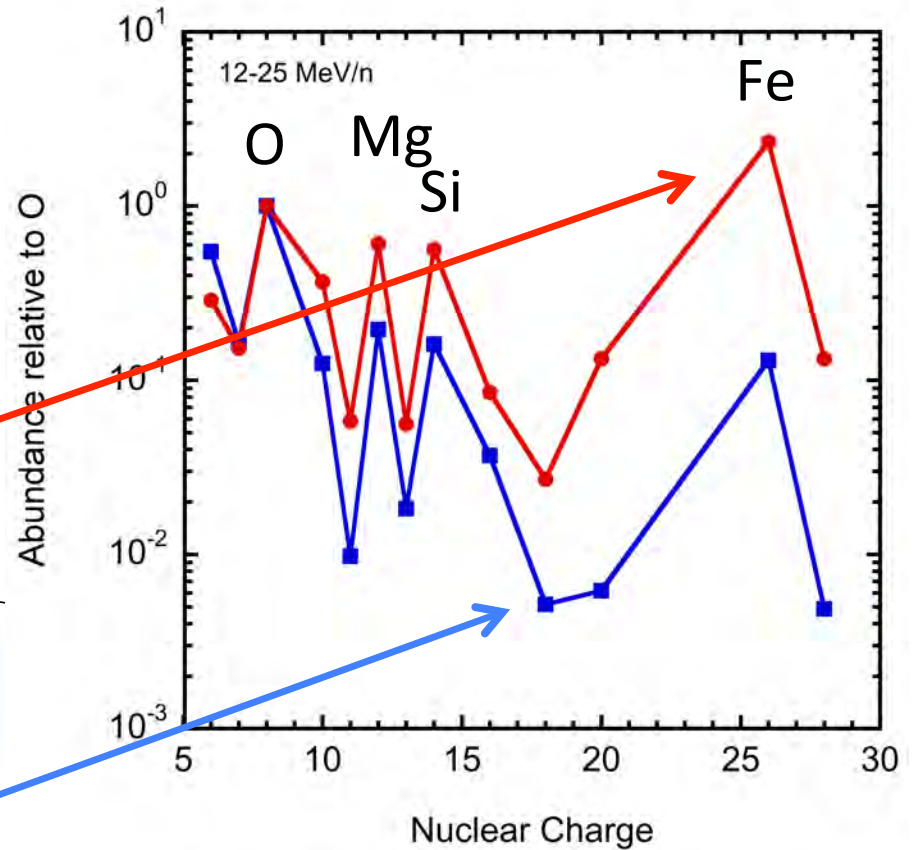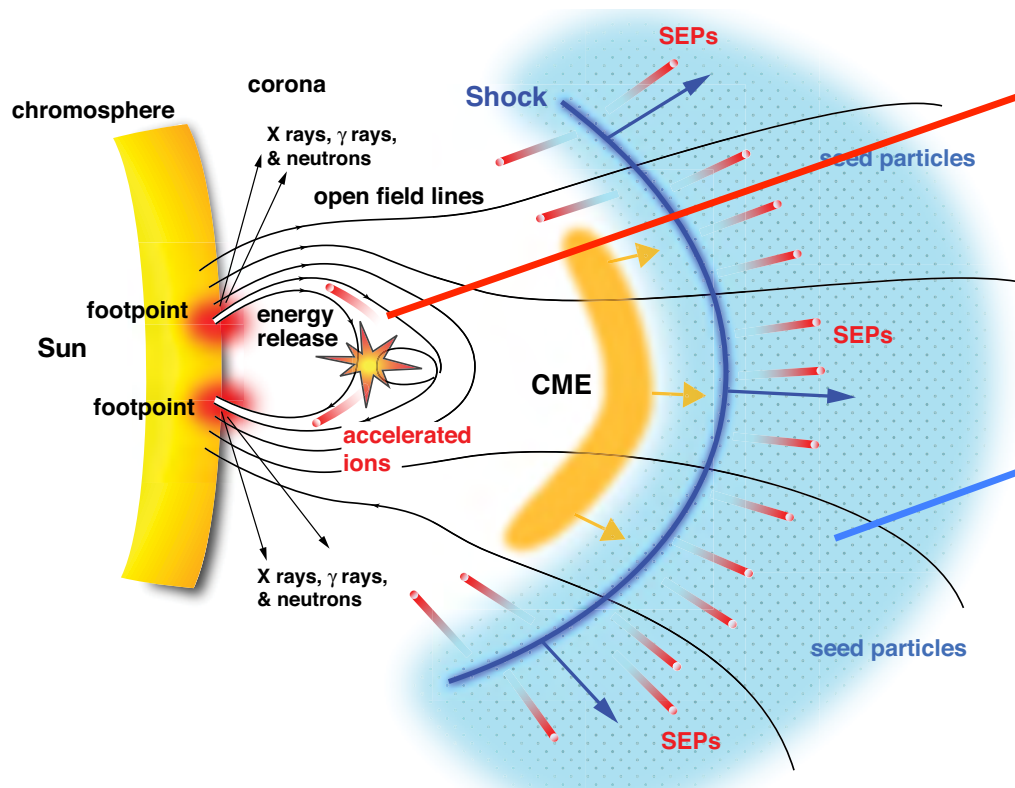
Shock/Upstream, Γ_I

Mass/Charge (AMU e^{-1})
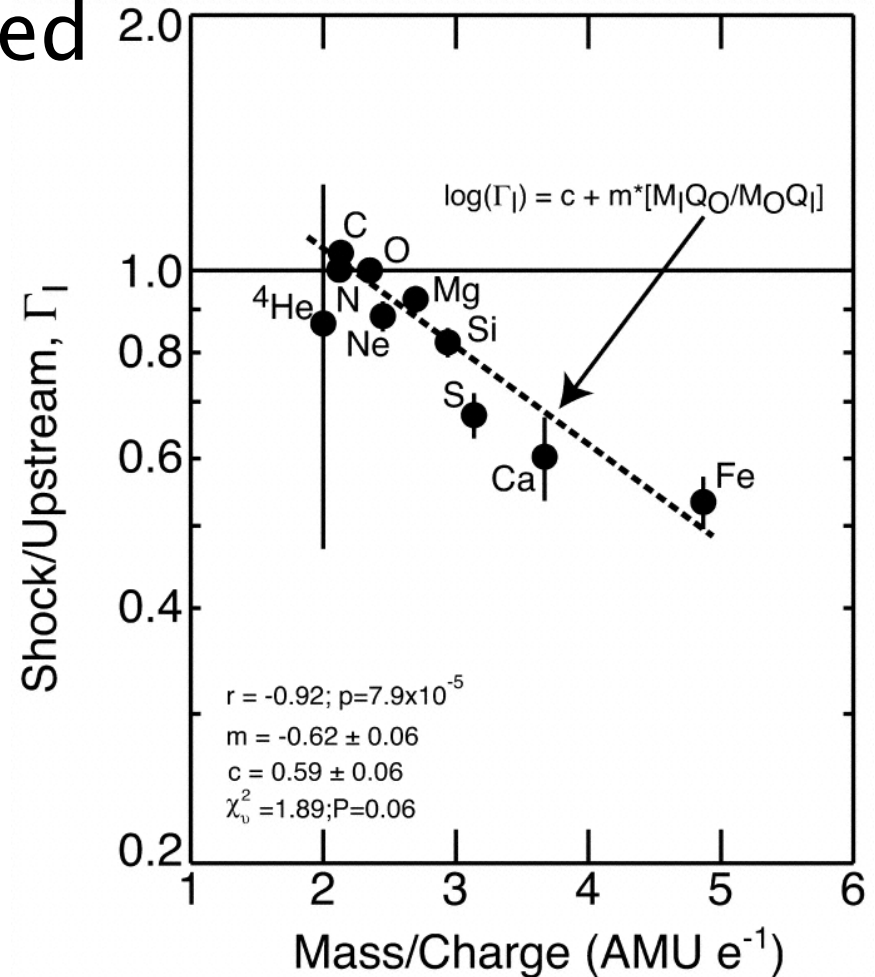
Origin

- Solar Wind & SEP have different composition
  - ^{3}He/^{4}He especially
- SEPs systematically related to upstream material
- Seed population is suprathermals

  - *What are its characteristics?*
  - *How does it vary?*

Contributions to the Oxygen Fluence
(10/97 to 6/00)

Slow Solar Wind

Fast Solar Wind

Suprathermal Tail

Gradual SEPs 11/97

CIR 1/00

Impulsive SEPs 11/97

ACRs (10/97-6/00)

Total (10/97 to 6/00)

GCRs

Particles/(cm^2 sr-MeV/nucleon)

Kinetic Energy (MeV/nucleon)

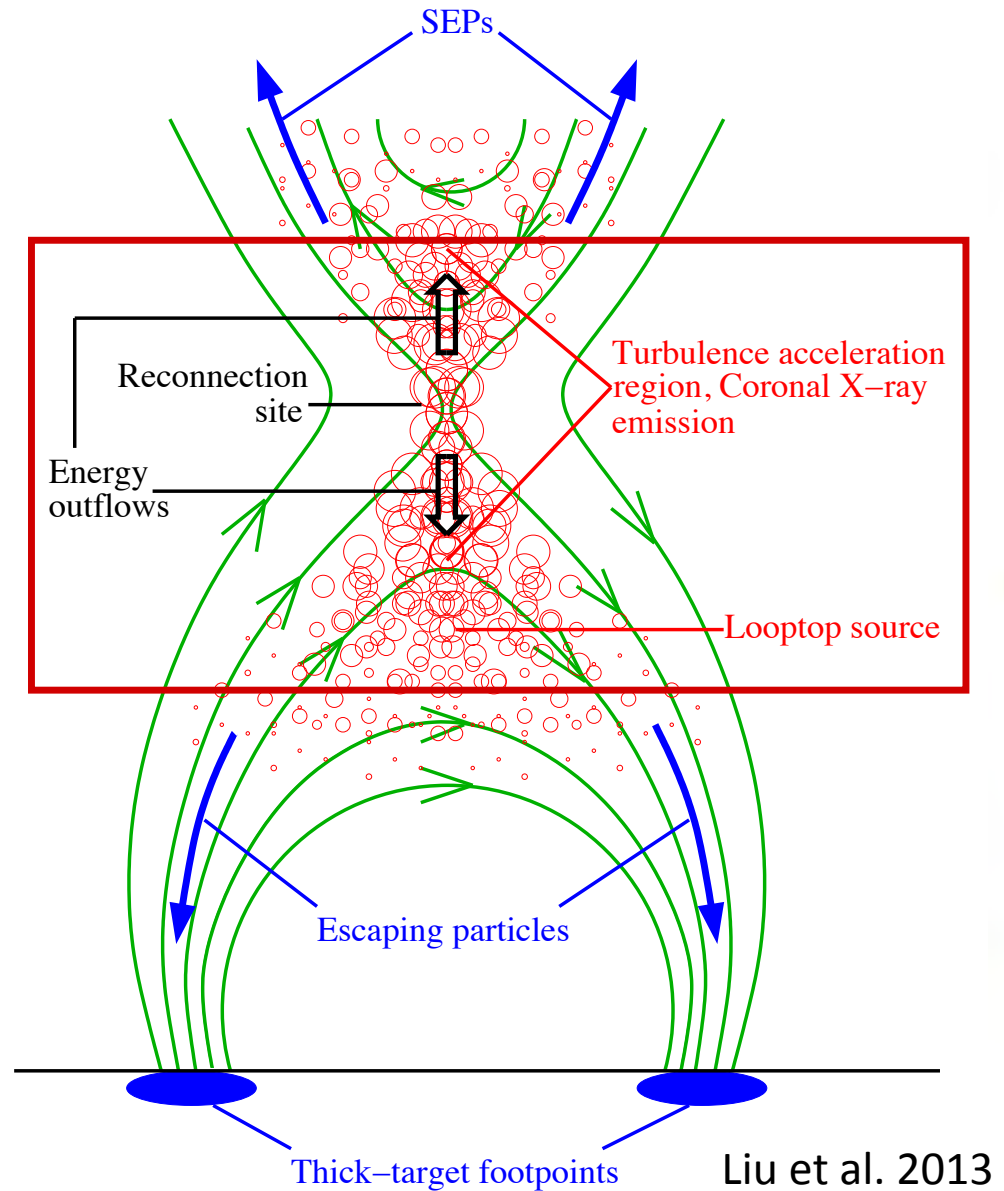SWIMS   ULEIS   SIS

SWICS   SEPICA   CRIS

Mewaldt et al. 2001

Acceleration

- 'Flare' processes
- CME-driven shocks

Acceleration

- 'Flare' processes
  - Turbulence stochastic

SEPs

Reconnection site

Energy outflows

Turbulence acceleration region, Coronal X–ray emission

Looptop source

Escaping particles

Thick–target footpoints

Liu et al. 2013
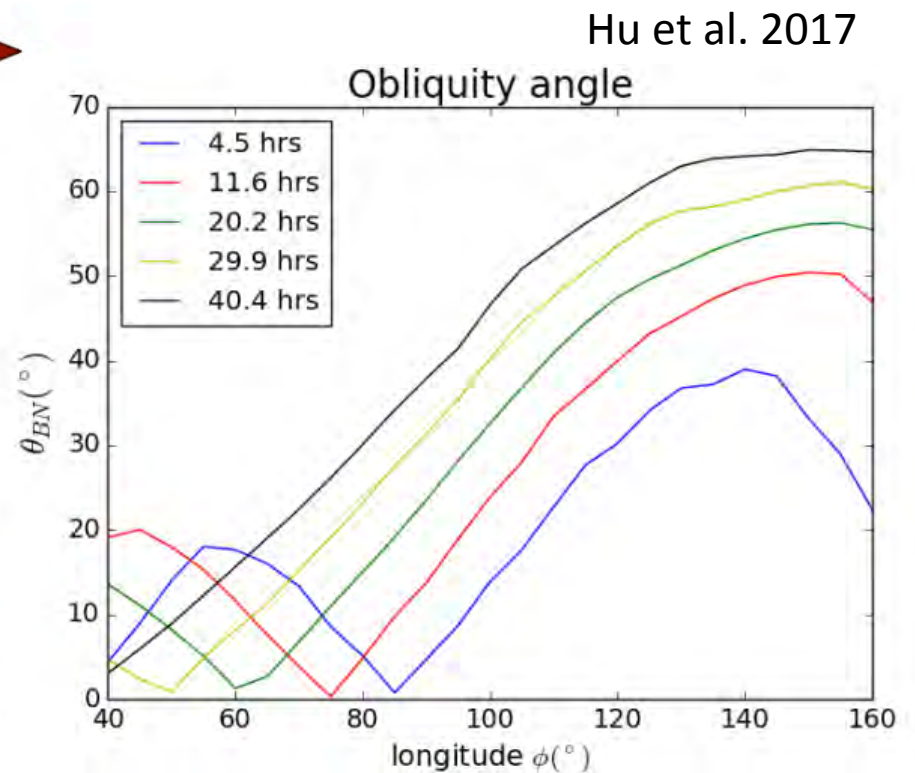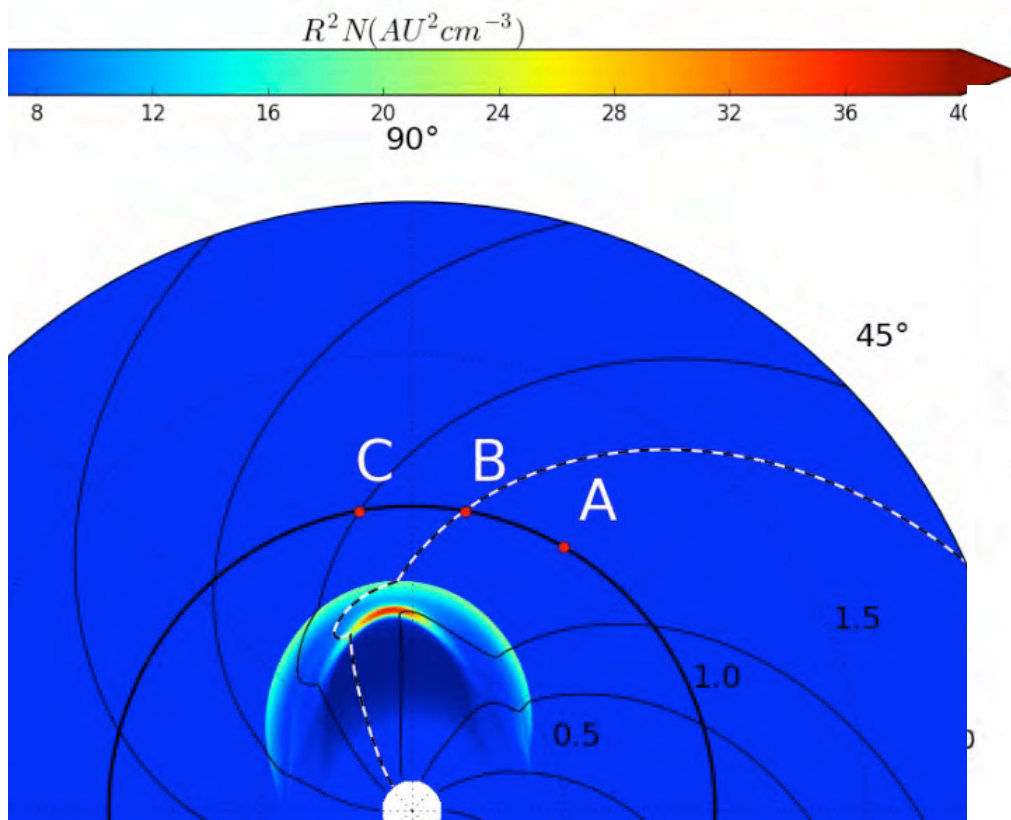
Acceleration

- 'Flare' processes
  - Turbulence stochastic
  - Magnetic islands
  - *Conditions in which this is occurring?*
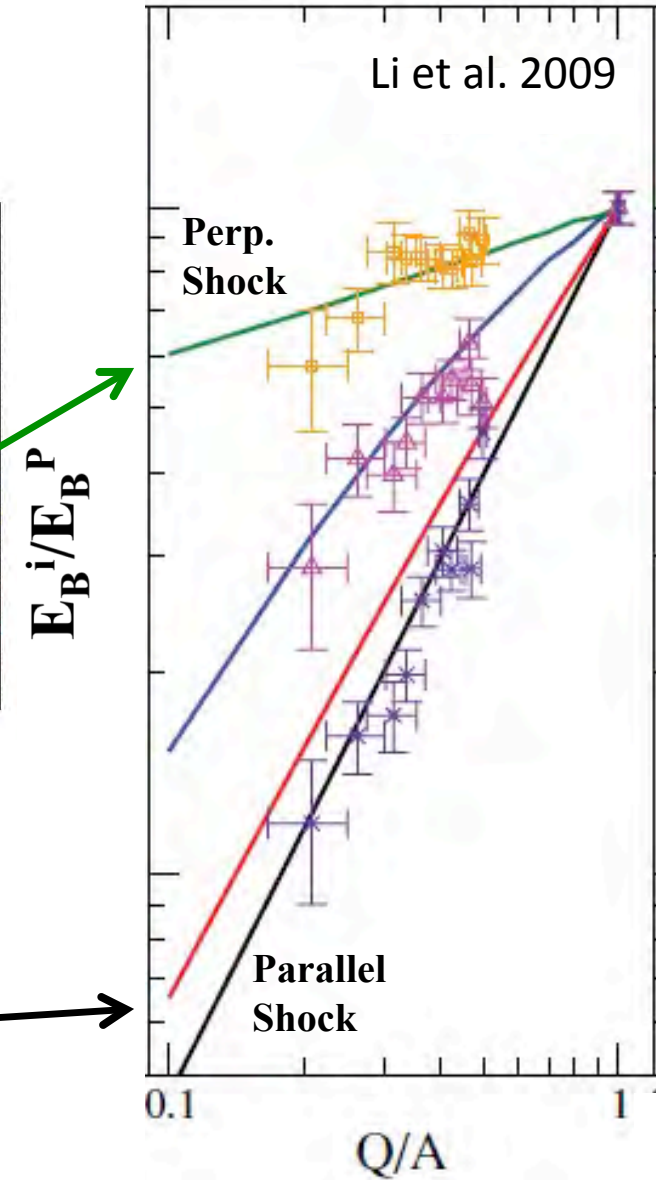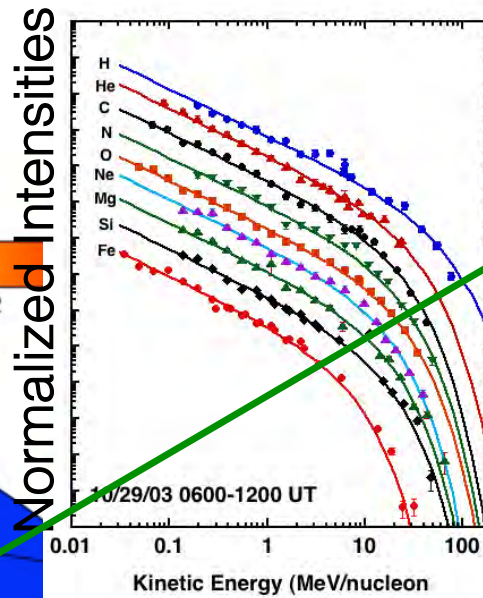 - *Heating of ^3He?*
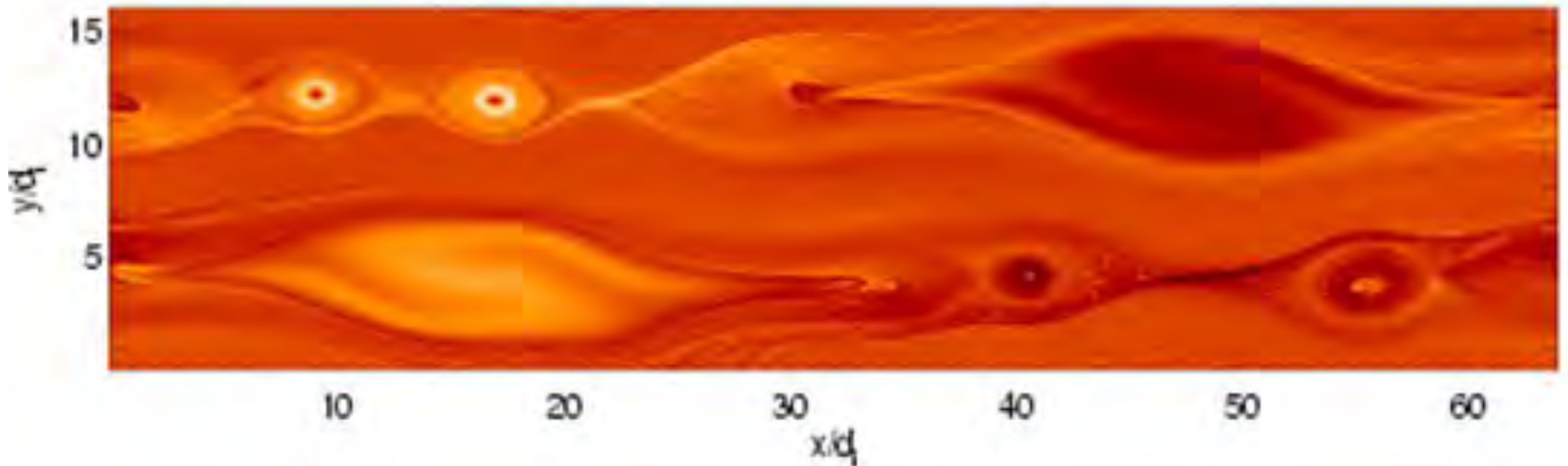
Drake et al. 2012

Acceleration

- CME-driven shocks
  - Orientation of the shock

Hu et al. 2017

Acceleration

- CME-driven shocks
  - Orientation of the shock
    - Spectra

Li et al. 2009

Acceleration

- CME-driven shocks
  - Orientation of the shock
    - Spectra
    - Composition

Tylka et al. 2005

Acceleration

- CME-driven shocks
  - Orientation of the shock
    - Spectra
    - Composition

- *Where exactly?*
  - *Nose?*
  - *Flanks?*

Rouillard et al. 2016

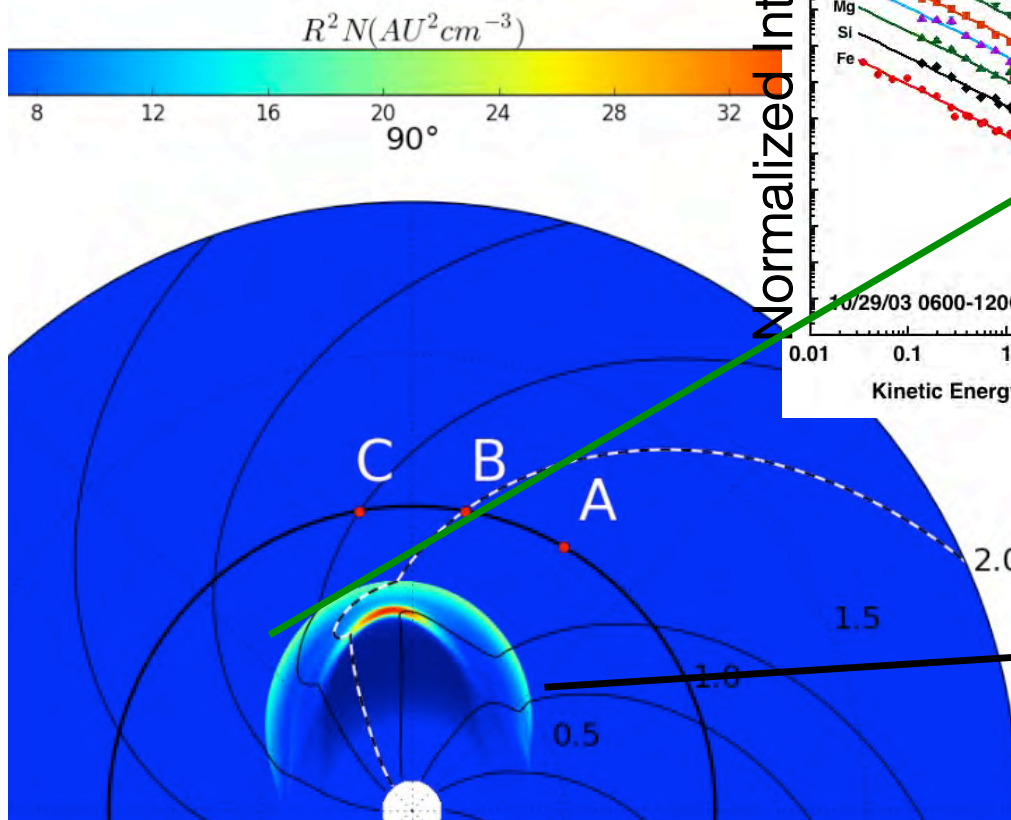# Acceleration

- CME-driven shocks
  - Orientation of the shock
    - Spectra
    - Composition

- *Where exactly?*
  - *Nose?*
  - *Flanks?*
- *Conditions?*
  - *Seed population*

Li et al. 2012

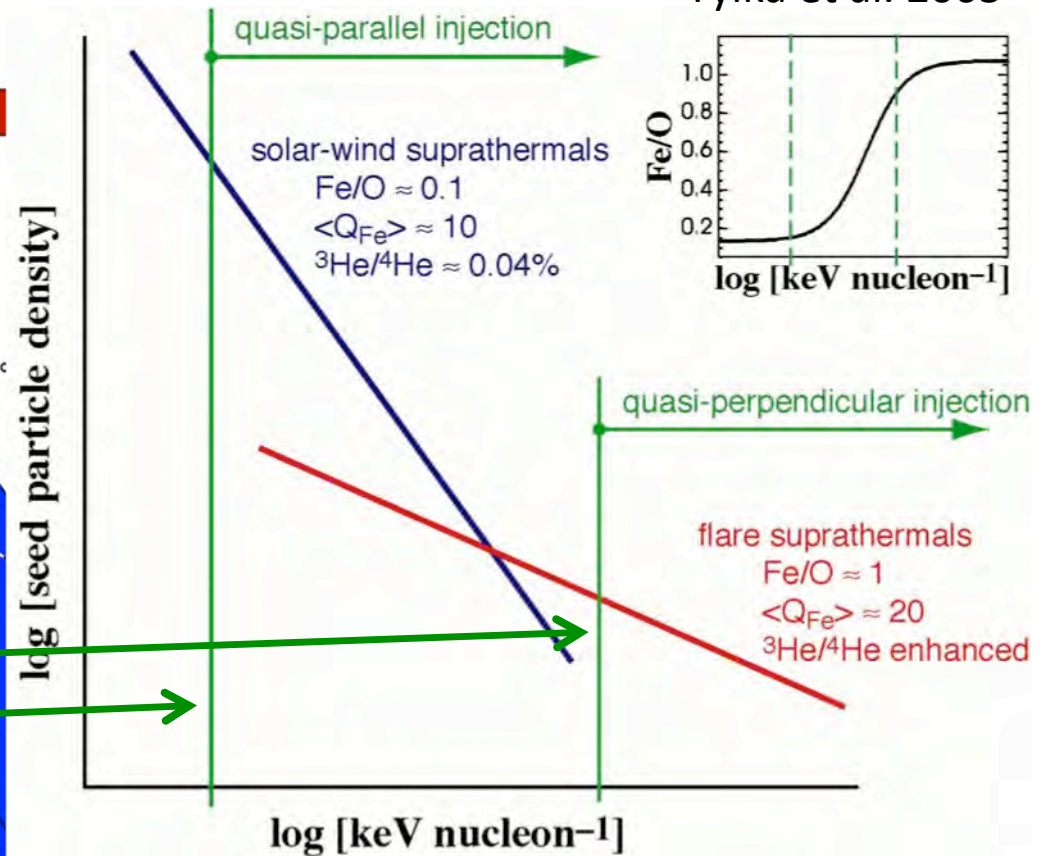# Acceleration

- CME-driven shocks
  - Orientation of the shock
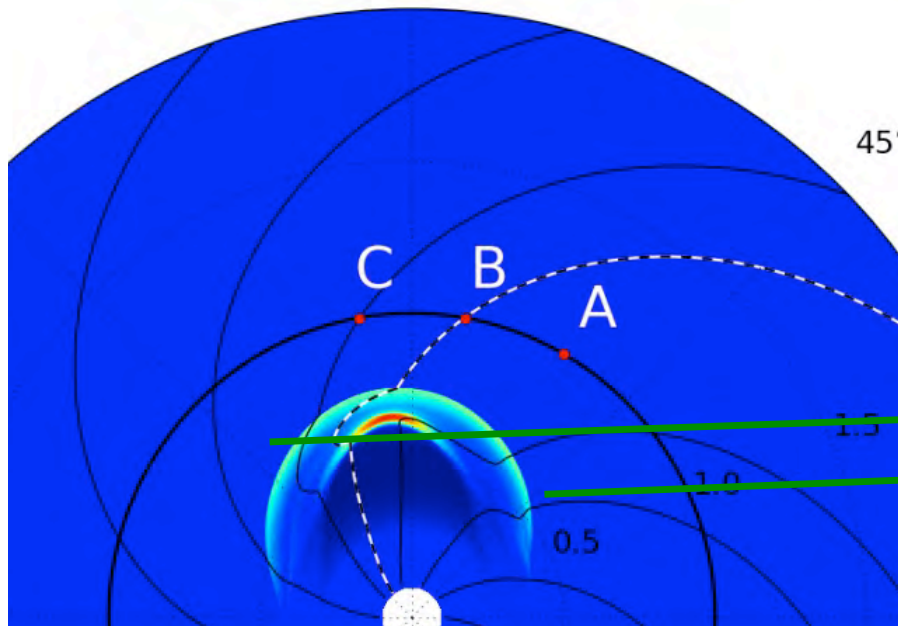   - Spectra
    - Composition
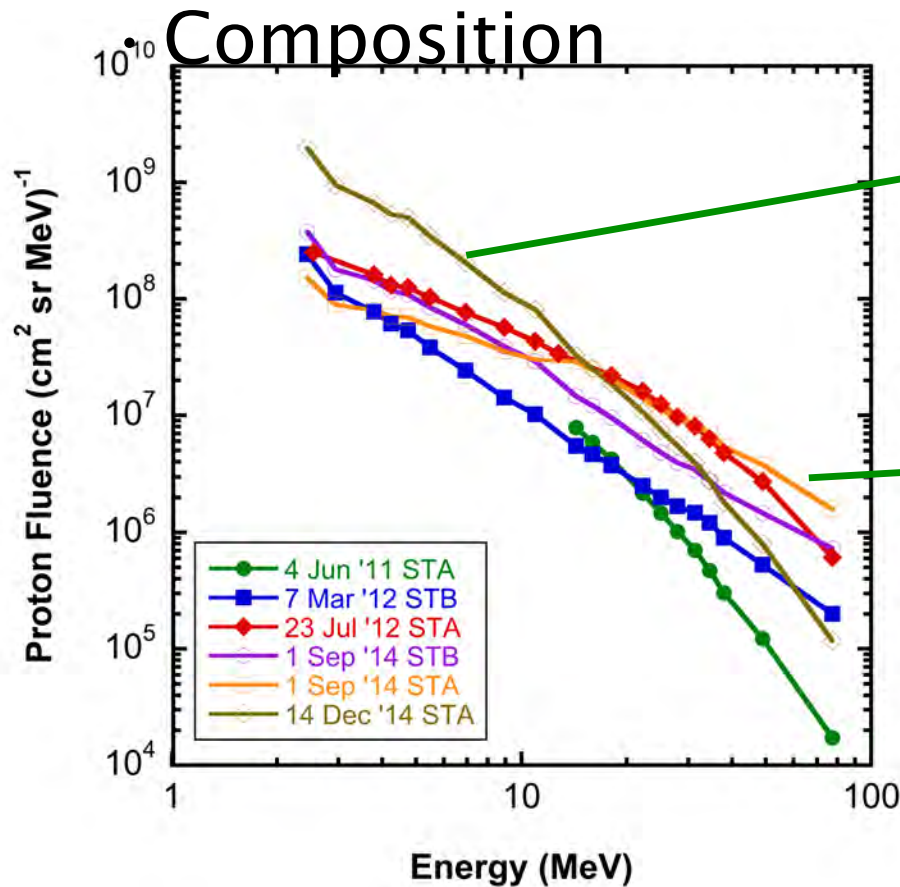
Cohen et

Acceleration

- CME-driven shocks
  - Orientation of the shock
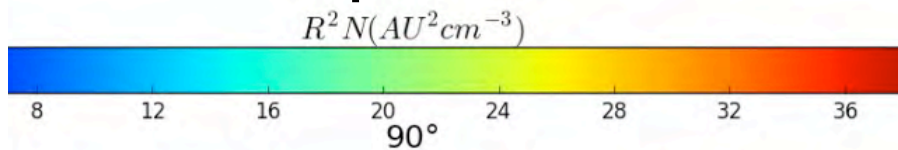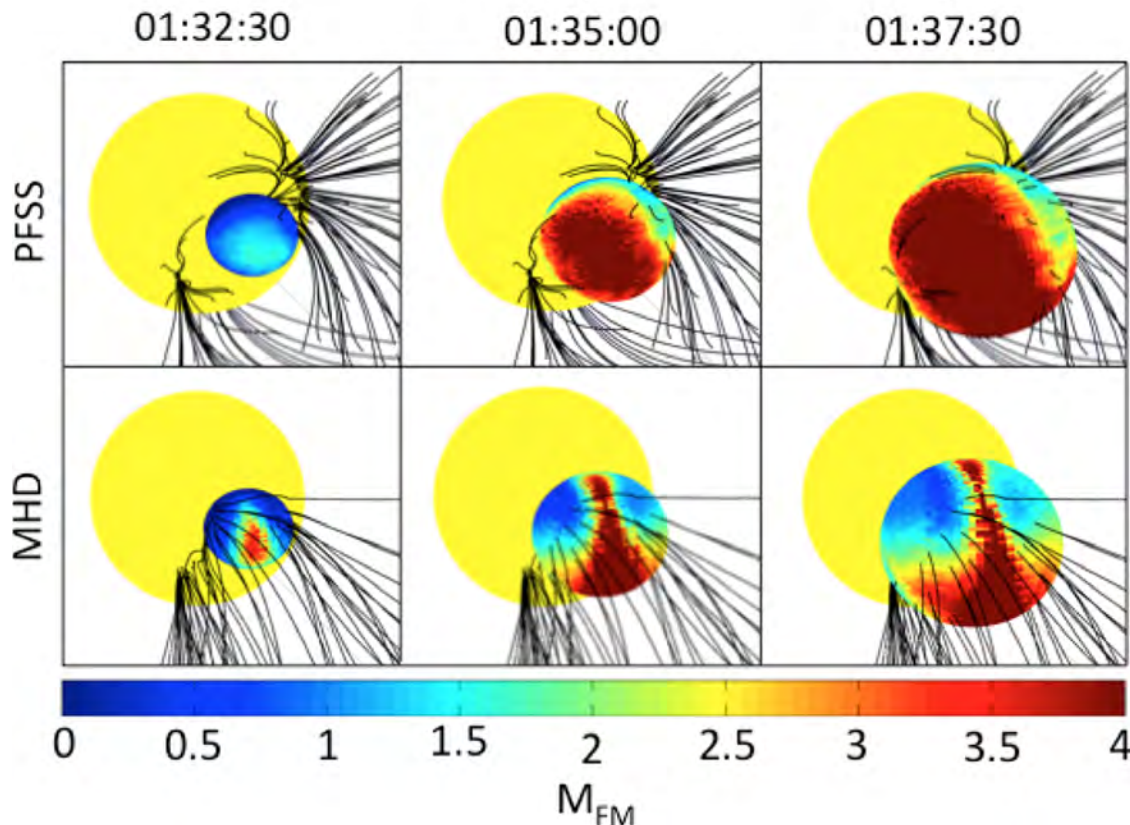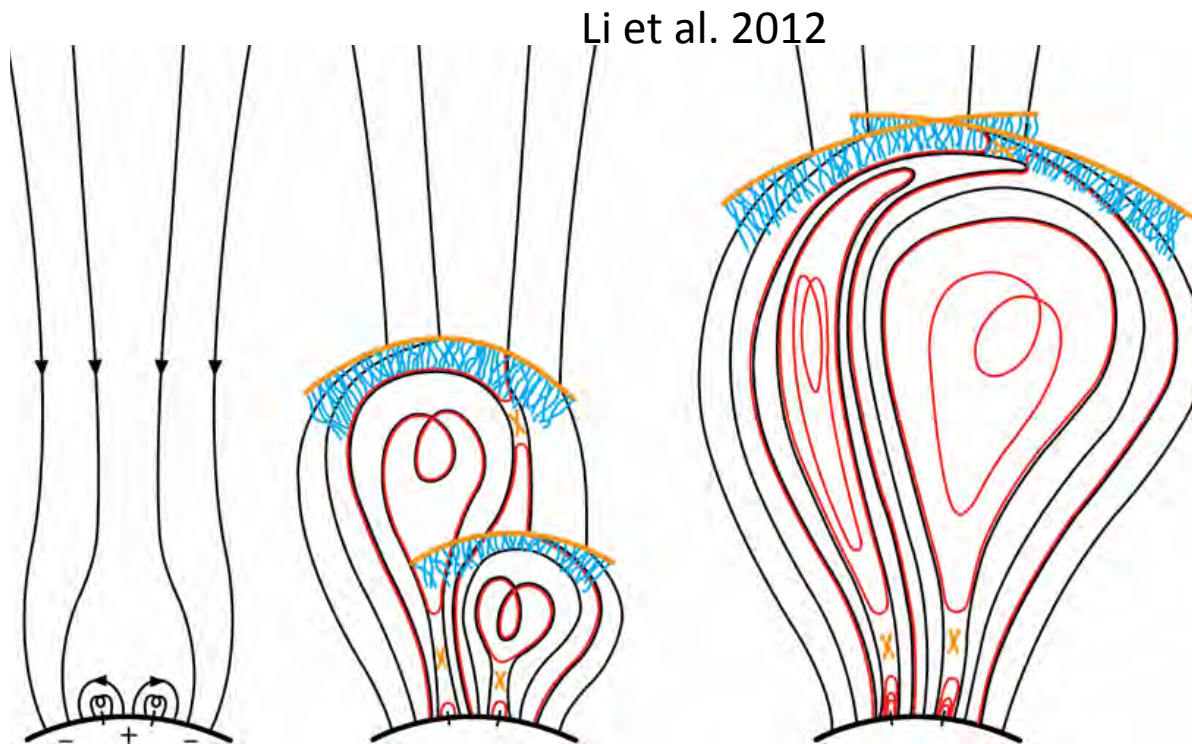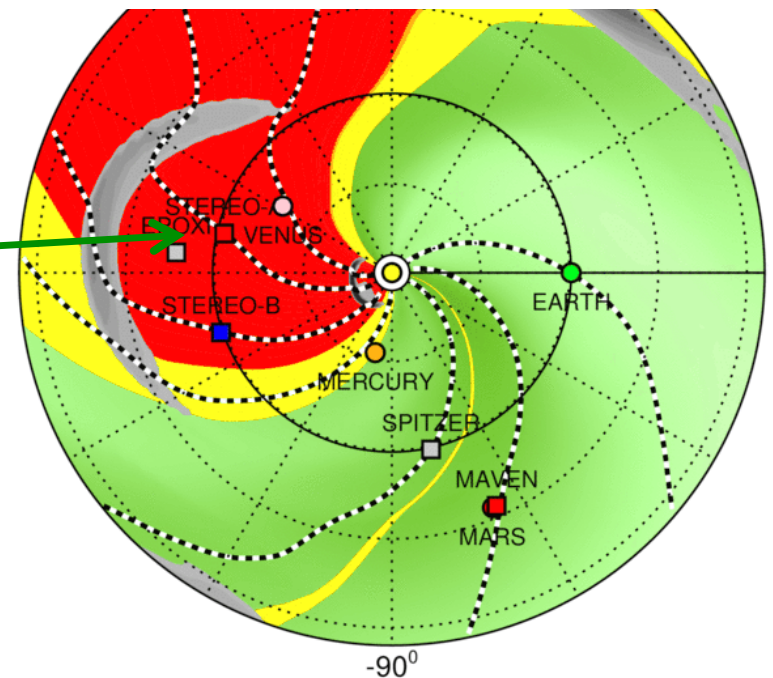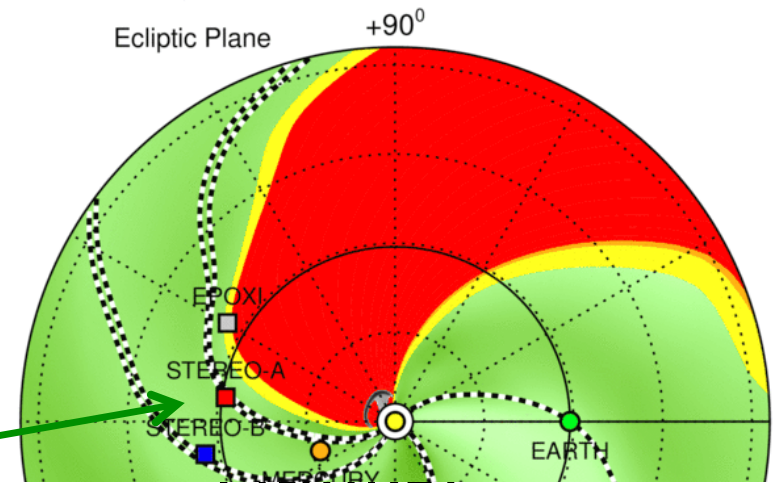   - Spectra
    - Composition
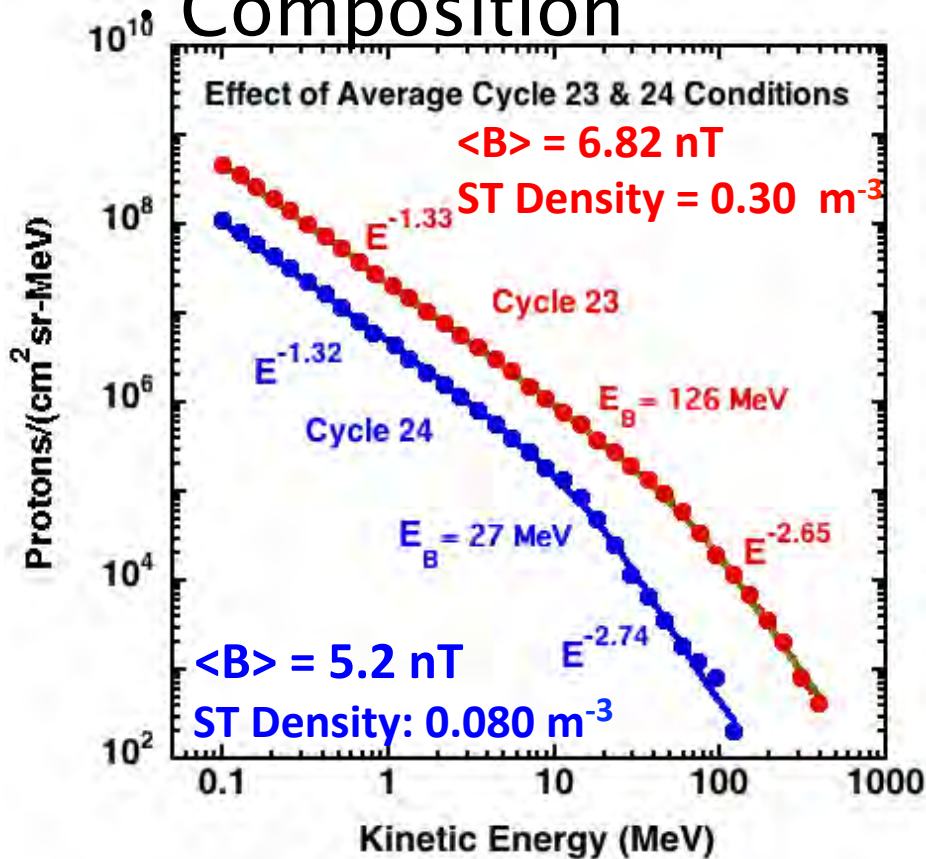
- *Where exactly?*
  - *Nose?*
  - *Flanks?*
- *Conditions?*
  - *Seed population*
  - *Magnetic connection*
  - *IPM*

Effect of Average Cycle 23 & 24 Conditions

$<B>$ = 6.82 nT
ST Density = 0.30 m^{-3}

$E^{-1.33}$

Cycle 23

$E^{-1.32}$

Cycle 24

E_B = 126 MeV

E_B = 27 MeV

$E^{-2.65}$

$E^{-2.74}$

$<B>$ = 5.2 nT
ST Density: 0.080 m^{-3}

Protons/(cm^2 sr-MeV)

Kinetic Energy (MeV)

Mewaldt et al. 2017

Transport

- Governed by rigidity

Mason et al. 2012

Transport

- Governed by rigidity
- But not for longitude?
  - No clear Q/M trend
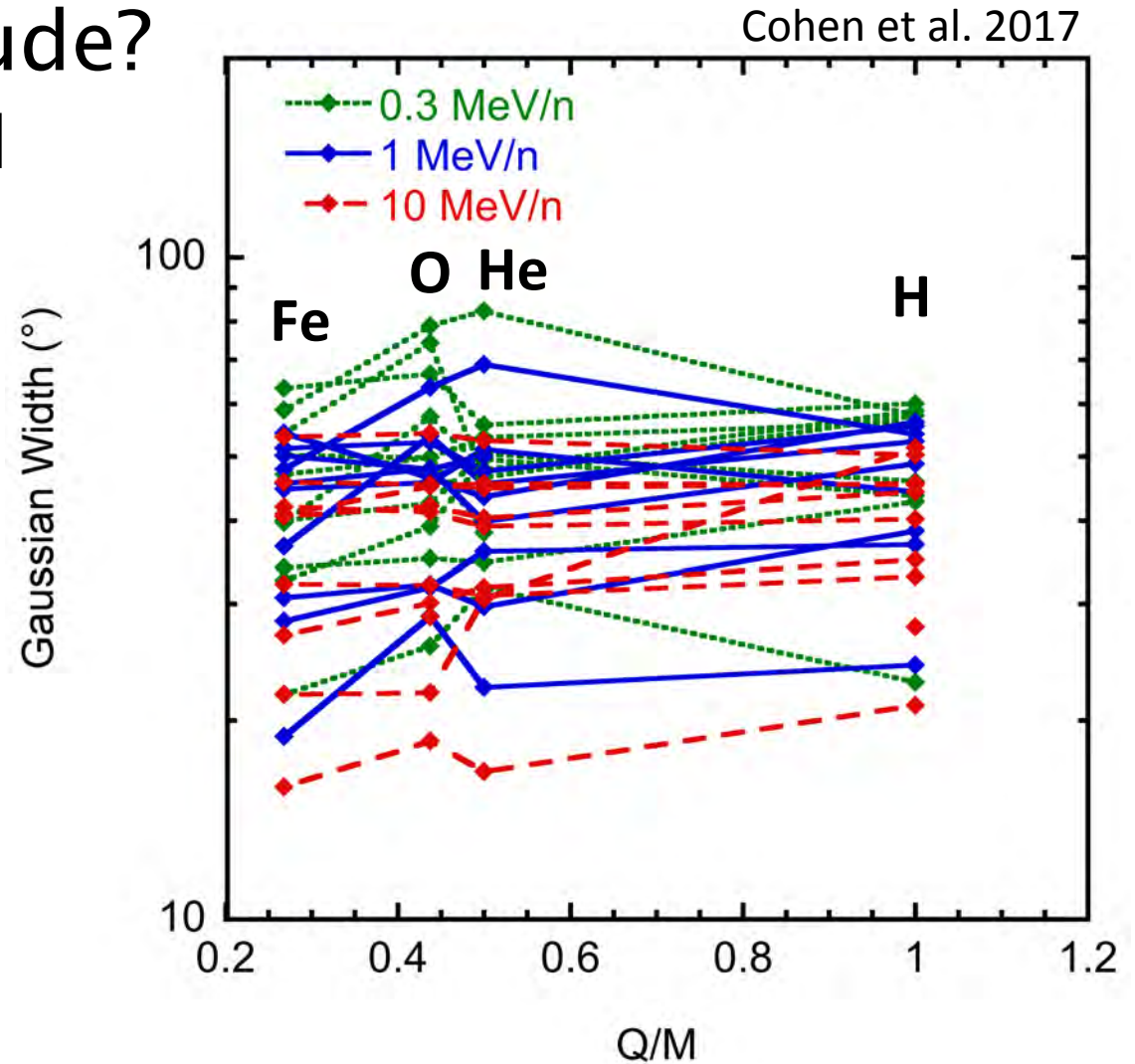
Cohen et al. 2017

Transport

- Governed by rigidity
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Cohen et al. 2017

Transport

- Governed by rigidity
- But not for longitude?
  - No clear Q/M trend
  - Clear E trend

Cohen et al. 2017

Transport

- Governed by rigidity
- But not for longitude?
  - No clear Q/M trend
  - Clear E trend
    - Narrower at higher E

Cohen et al. 2017
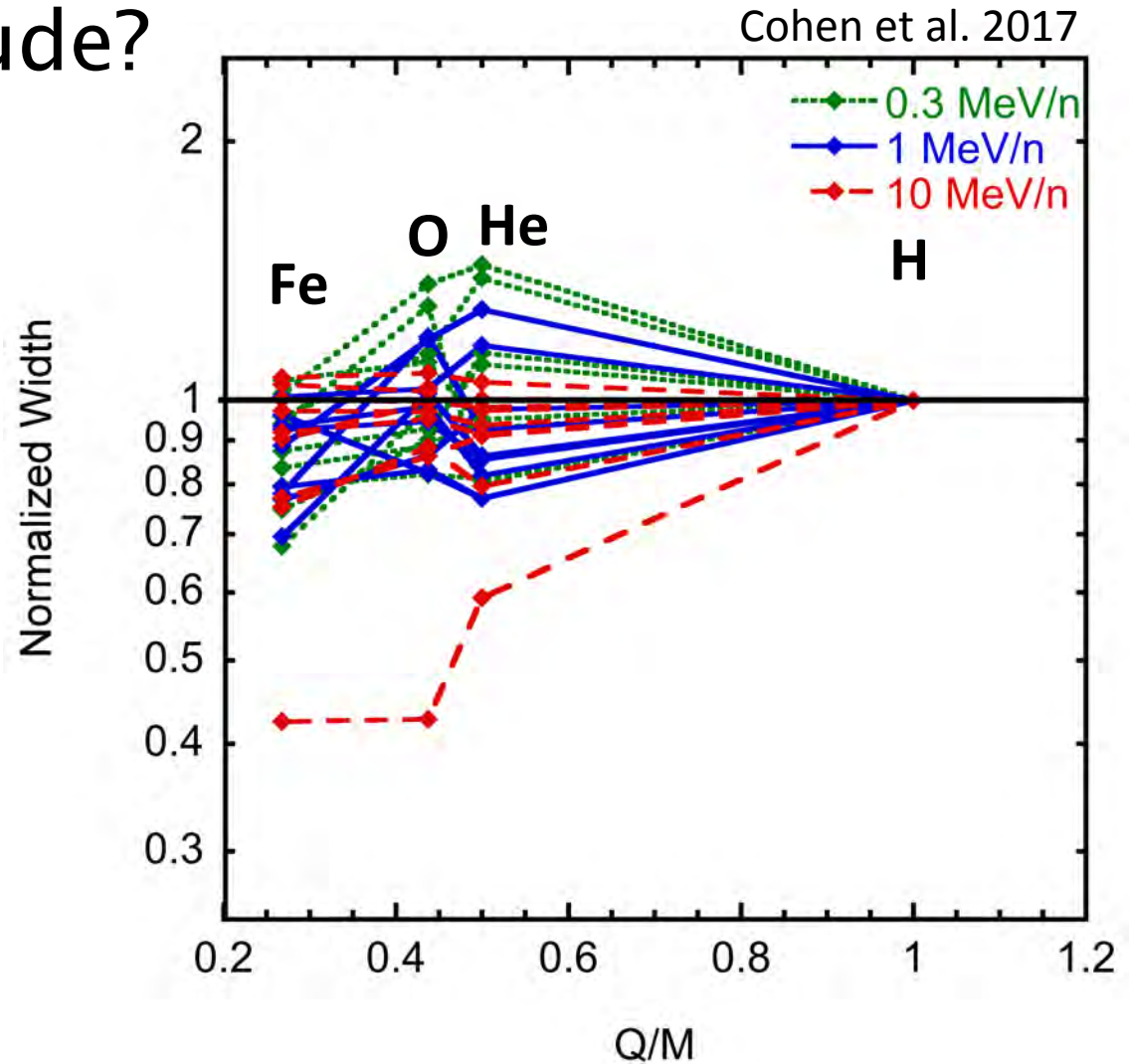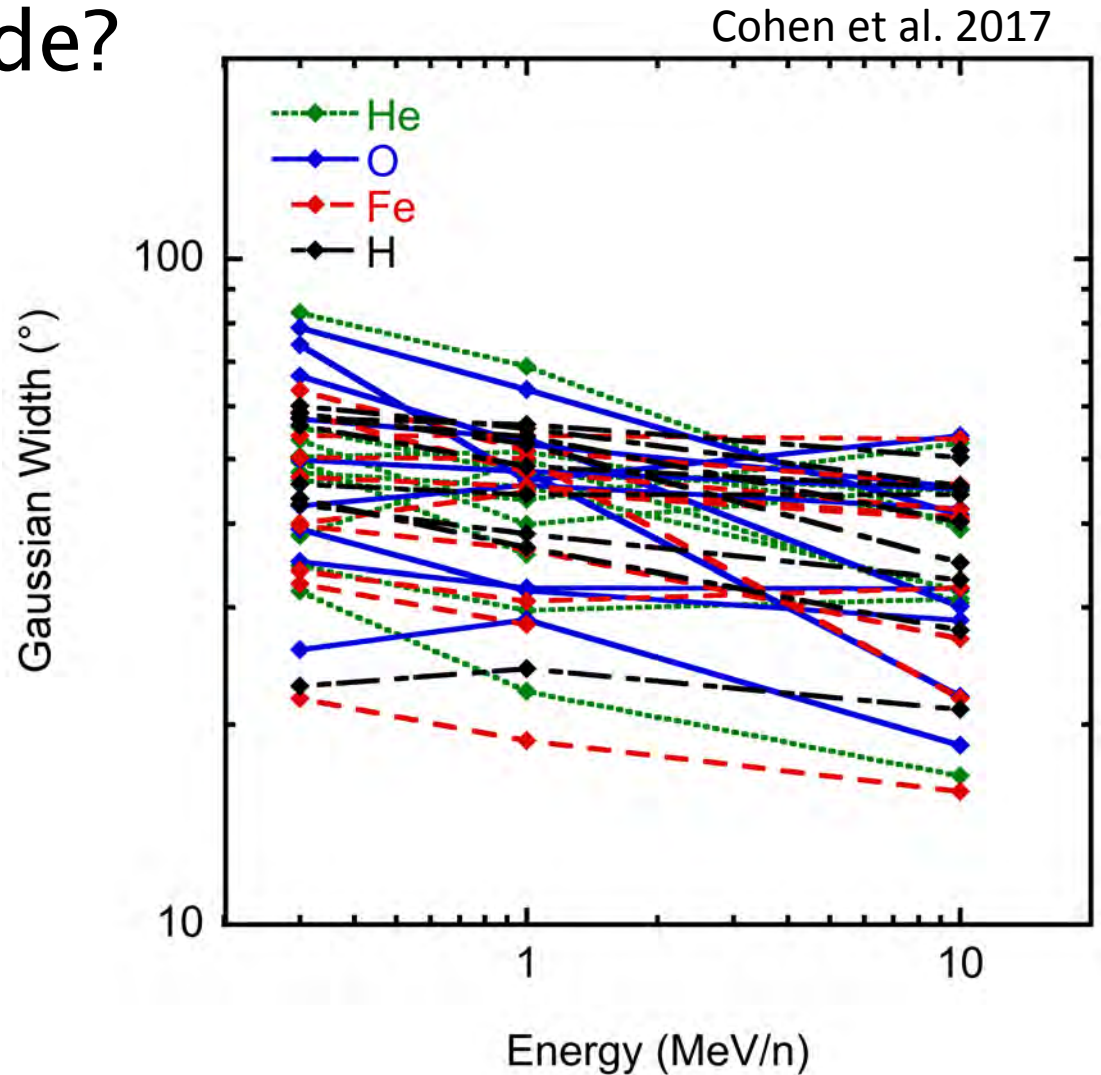
Transport

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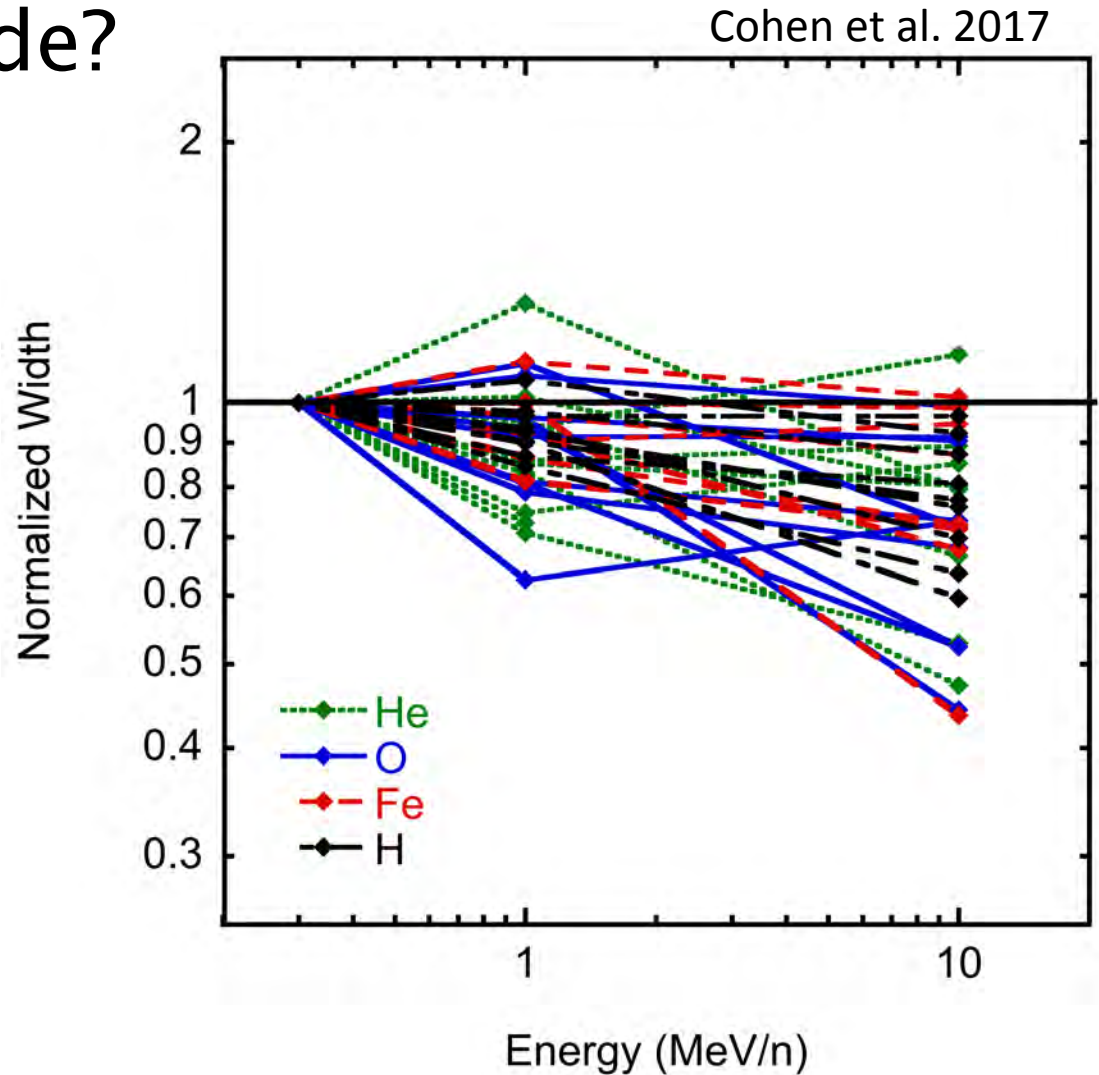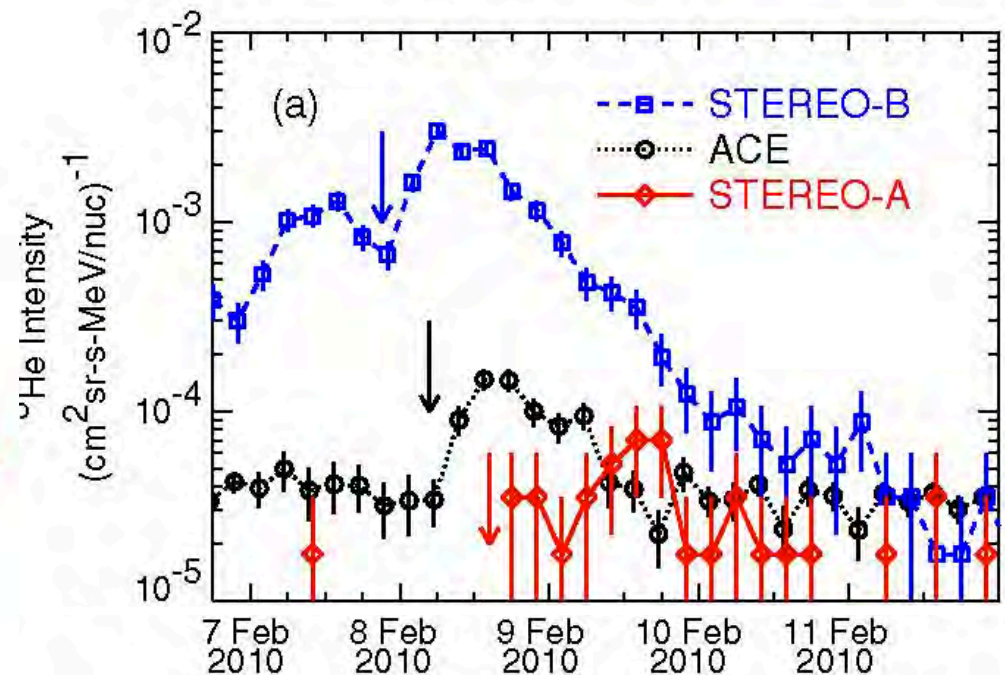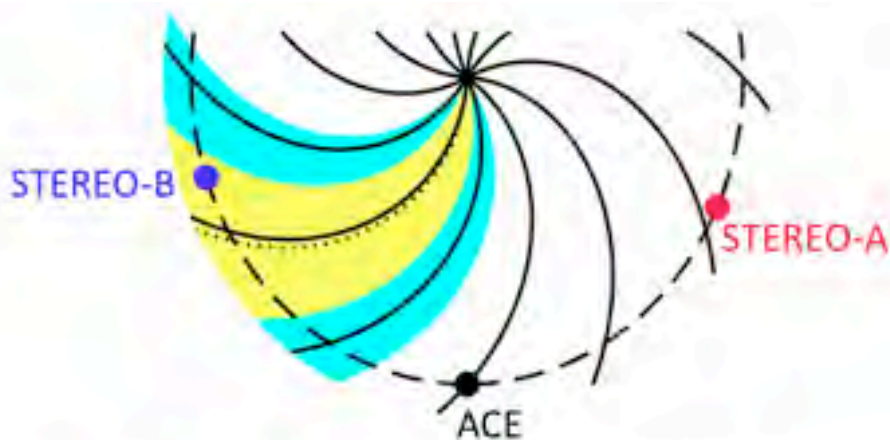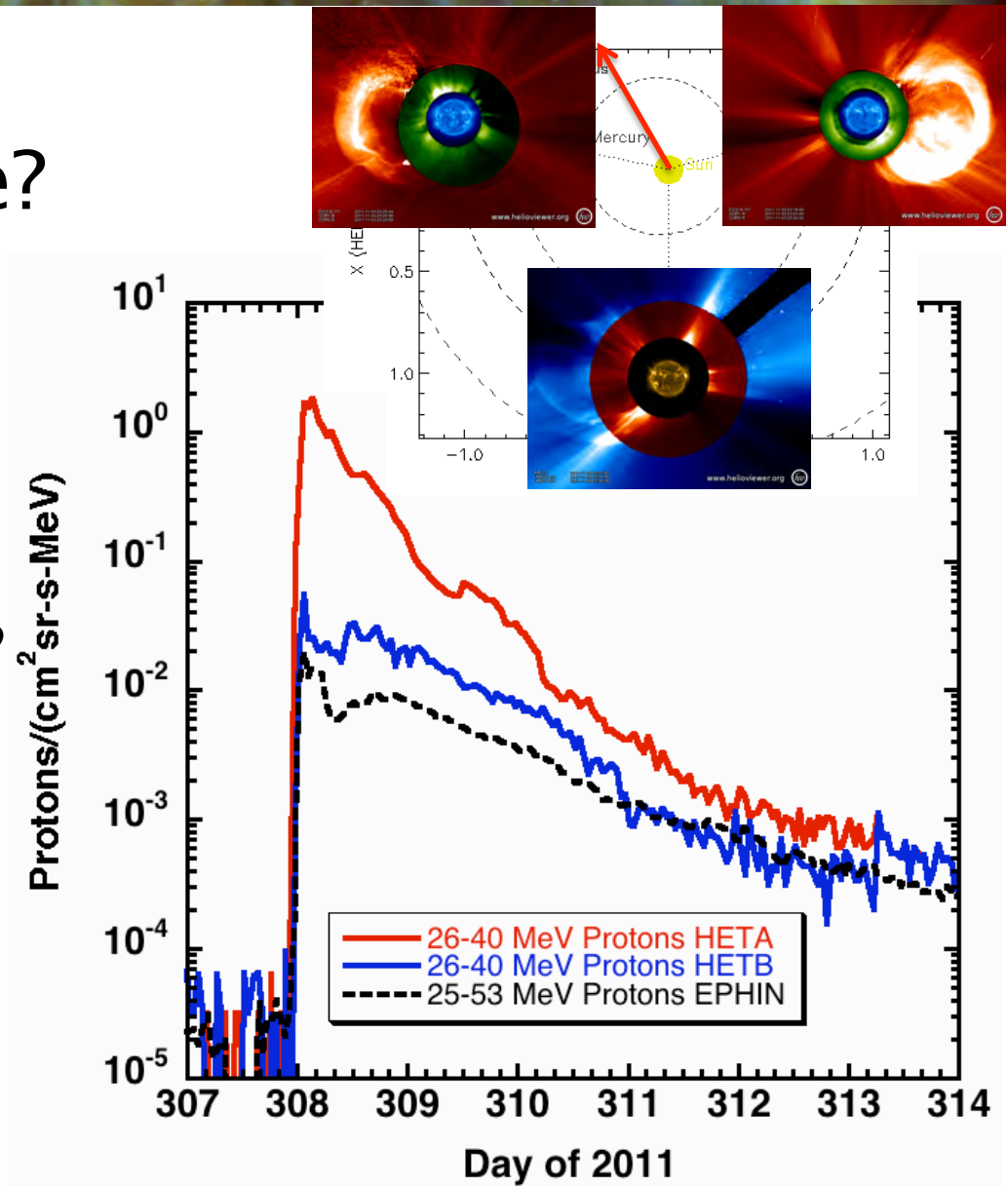- But not for longitude?
  - No clear Q/M trend
  - Clear E trend
    - Narrower at higher E
- *And what about this?*

T

- Governed by rigi
- But not for long
  - No clear Q/M tre
  - Clear E trend
    - Narrower at higher E
- *And what about this?*
- *And this?*

	STEREO-B	Earth
Heliocentric ... e (AU)	1.085968	0.992181
Semidiameter ...)	883.661	967.190
HCI longitude	222.157	324.503
HCI latitude	4.699	4.224
Carrington longitude	72.894	175.240
Carrington rotation number	2116.798	2116.513
Heliographic (HEEQ) longitude	-102.346	-0.000
Heliographic (HEEQ) latitude	4.699	4.224
HAE longitude	298.135	40.052
Earth Ecliptic (HEE) longitude	-101.916	-0.000
Earth Ecliptic (HEE) latitude	-0.183	0.000
Roll from ecliptic north	0.039	

10^9

Nov 3, 2011

What We Know & *Don't*

- Origin is the suprathermals
  - *Composition, spectrum, variability*
- Acceleration is mostly by CME-driven shocks
  - *Location on the shock, orientation*
  - *Seed population*
  - *Magnetic connection, IPM conditions*
- Transport is governed by rigidity

What We Know & *Don't*

- Origin is the suprathermals
  - *Composition, spectrum, variability*
- Acceleration is mostly by CME-driven shocks
  - *Location on the shock, orientation*
  - *Seed population*
  - *Magnetic connection, IPM conditions*
- Transport is ~~governed by rigidity~~ complicated
  - *Dependence on energy*
  - *Longitudinal distribution*
- Parker Solar Probe & Solar Orbiter will help

There will be new surprises

Thank You