

Solar Energetic Particles and Solar Events - Lessons Learned from Multi-spacecraft Observations

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Solar Energetic Particles and Solar Events - Lessons Learned from Multi-spacecraft Observations

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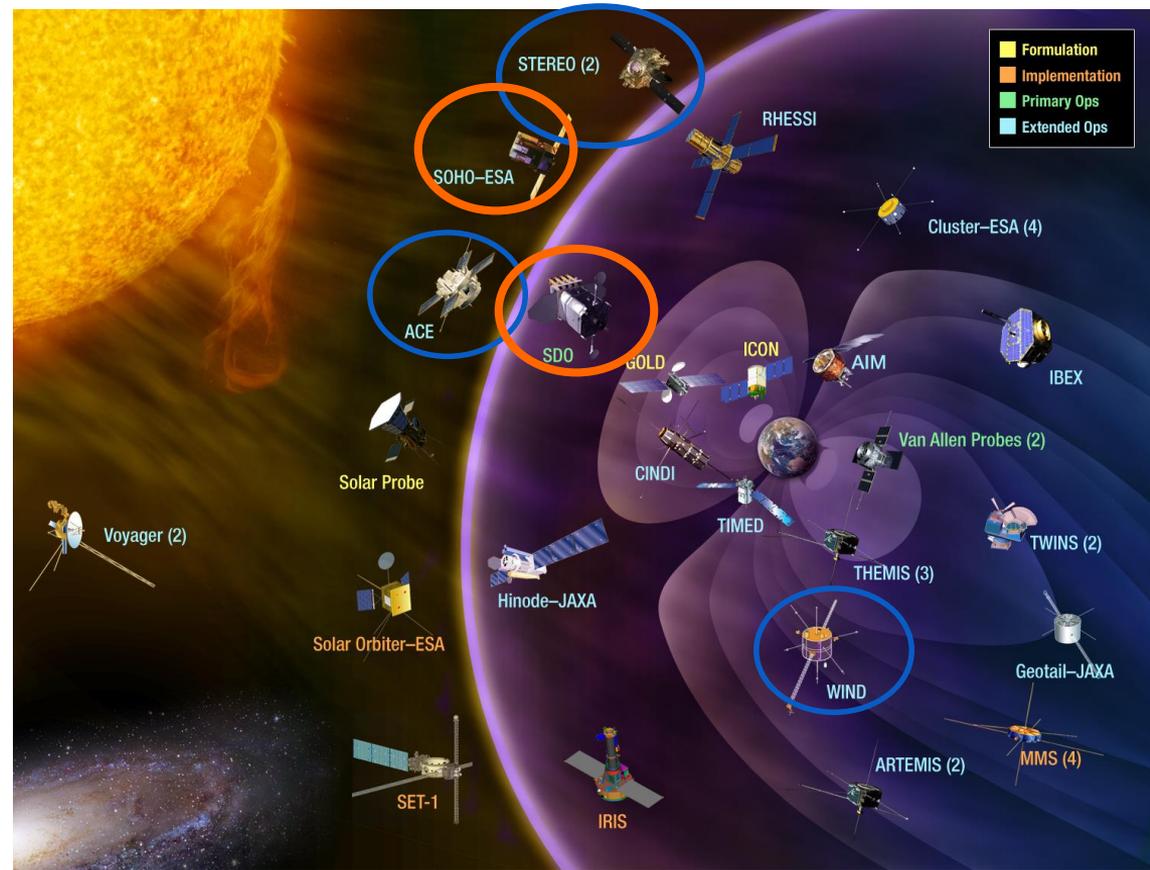


Outline

- Multi-spacecraft Capabilities
 - STEREO, ACE, Wind, GOES, SDO, SOHO...
 - Remote & in-situ measurements
- New regimes = New puzzles
 - Space (longitude)
 - Time (solar cycle 24)
- Open Questions and Future Opportunities

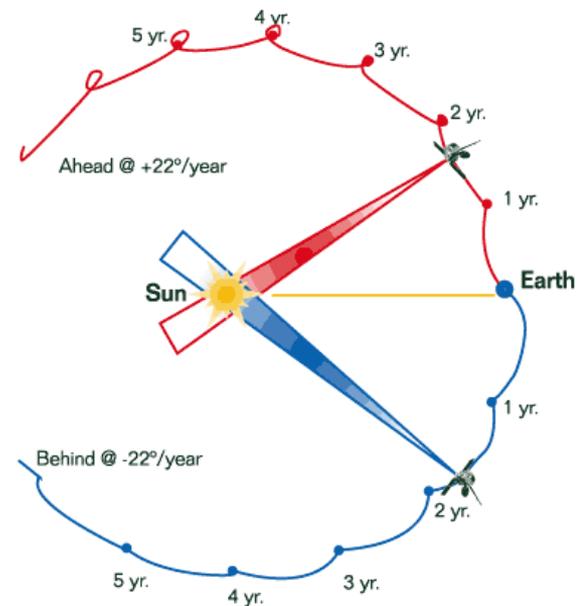
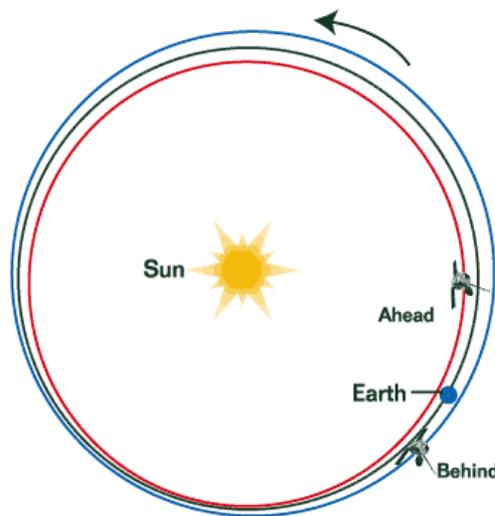
Multiple Spacecraft

- Heliosphysics System Observatory
- Sun to Mud
- Focus on
 - STEREO
 - ACE, GOES, Wind
 - SOHO, SDO



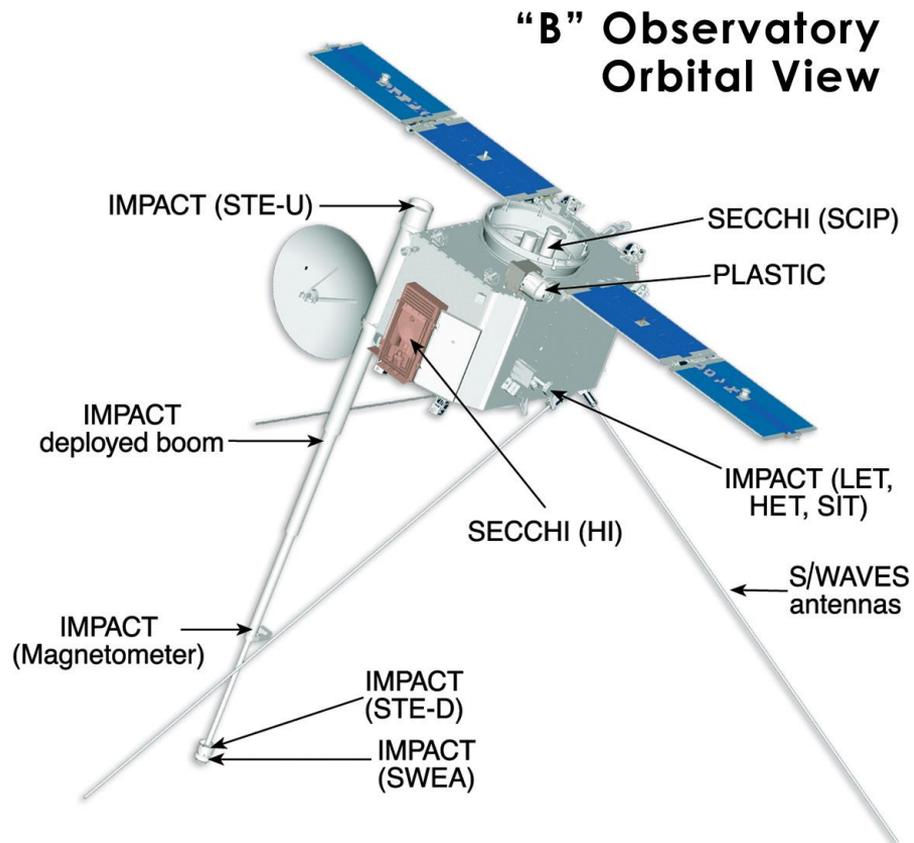
STEREO

- Launches 25 October 2006
- Twin spacecraft
 - Separate at $22.5^\circ/\text{year}$ from Sun-Earth line



STEREO

- Launches 25 October 2006
- Twin spacecraft
 - Separate at 22.5° /year from Sun-Earth line
 - Imaging, particle, & fields sensors



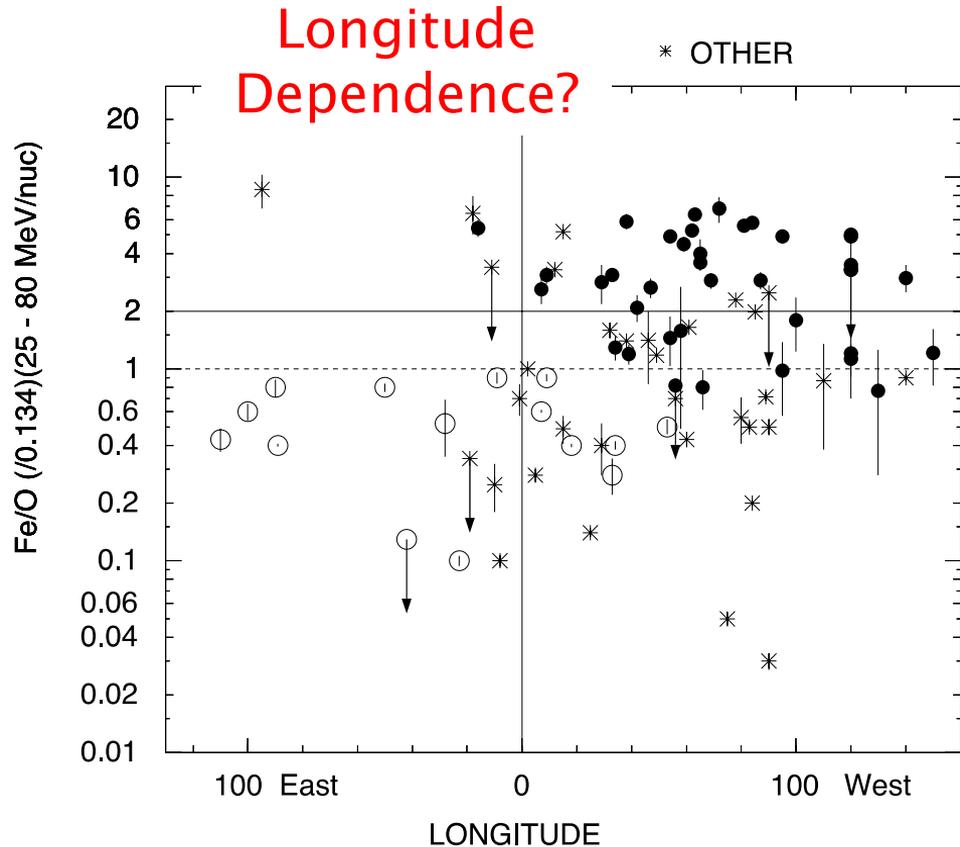
STEREO

- Launches 25 October 2006
- Twin spacecraft
 - Separate at 22.5° /year from Sun-Earth line
 - Imaging, particle, & fields sensors
 - SEP coverage is similar to ACE

Particles	STEREO	ACE
Protons	2-100 MeV	0.05-5 MeV
Helium	0.1-100 MeV/n	0.1-40 MeV/n
Heavy Ions	0.3-100 MeV/n	0.2-100 MeV/n
Electrons	35-6000 keV	35-300 keV

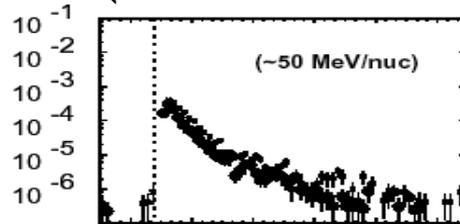
Expanding View

- Limitations of a single point of view
 - SEP observations mostly from along the Sun-Earth line
 - Can only determine where the solar source region is (often front side)

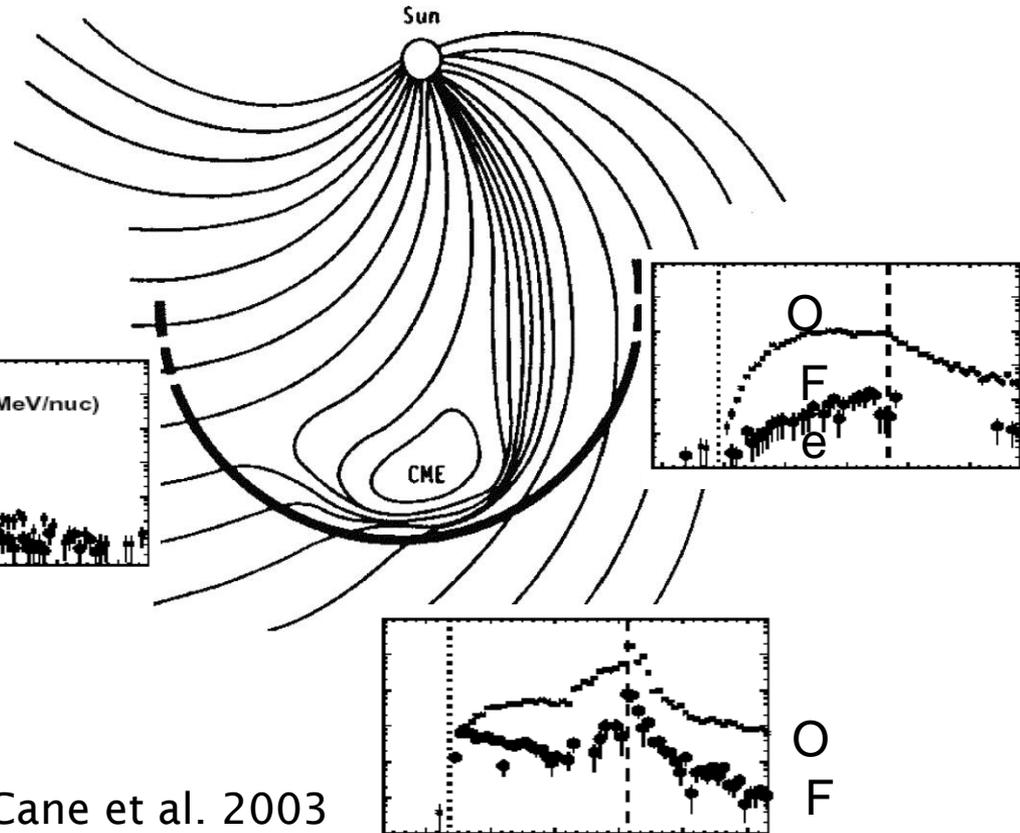


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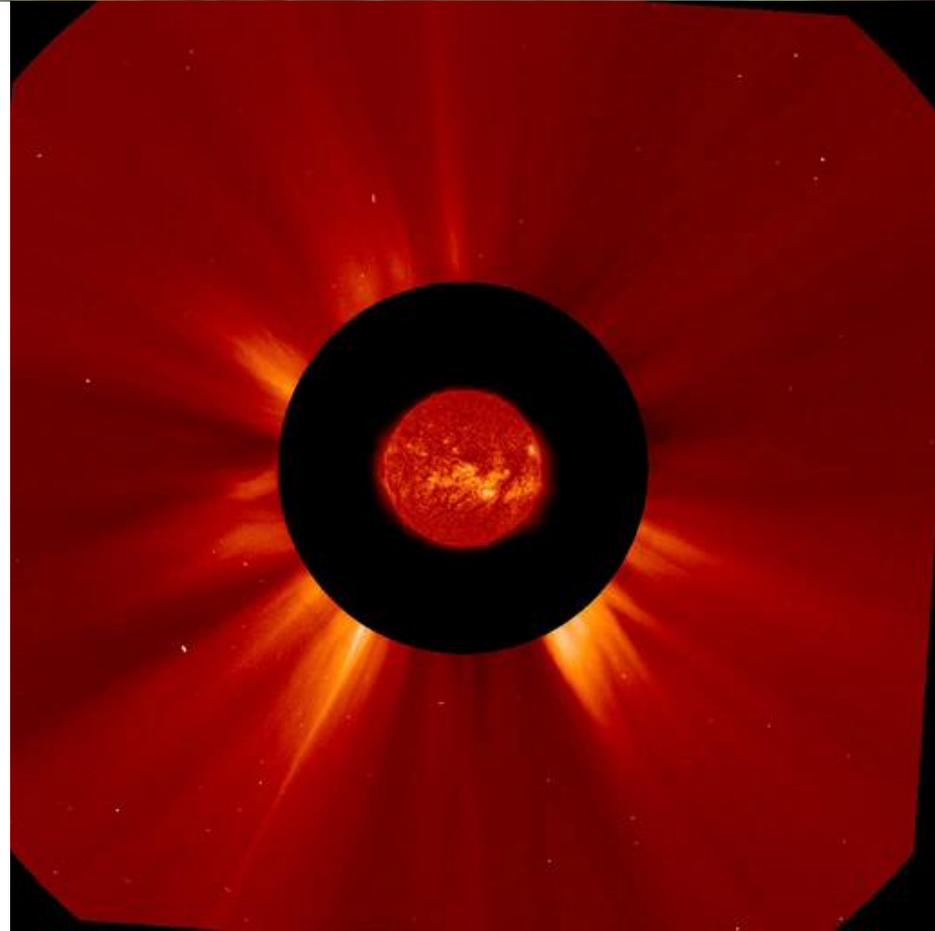
Simultaneous, multiple views



- Multiple longitude views
 - SEP characteristics

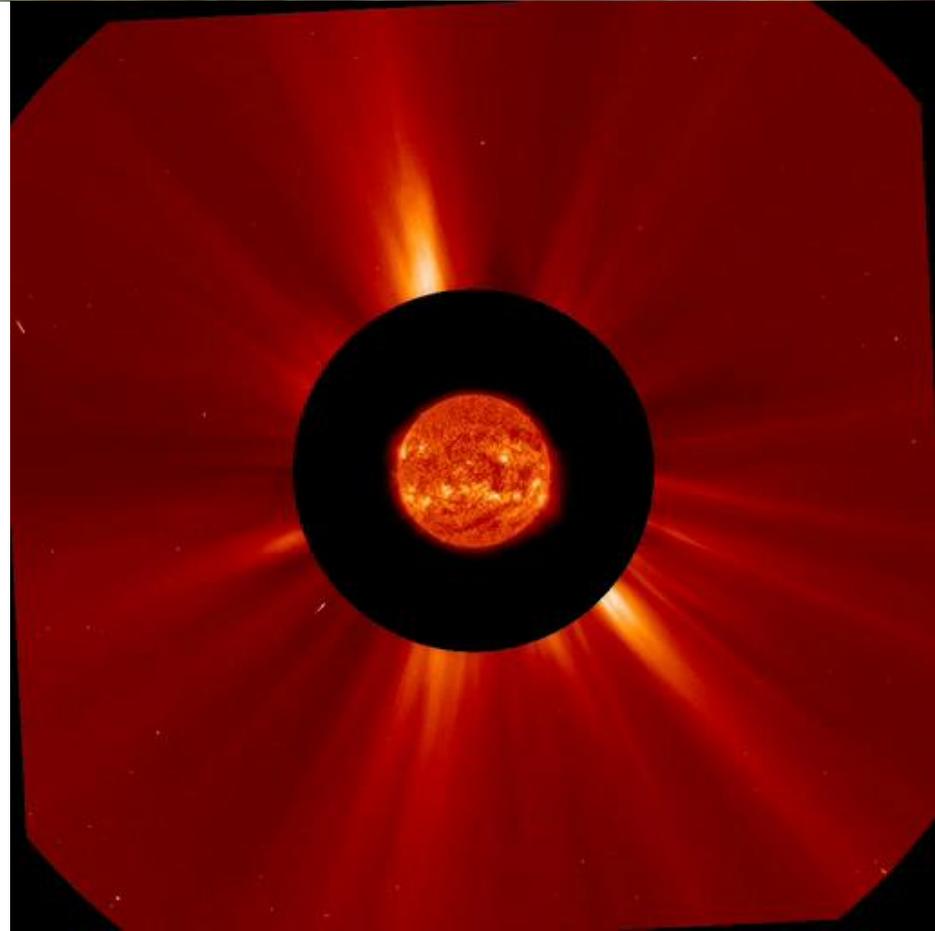
Expanding View

- Limitations of a single point of view
 - SEP observations mostly from along the Sun-Earth line
 - Can only determine where the solar source region is (often front side)
 - CME plane of sky speed
- Multiple longitude views
 - SEP characteristics



Expanding View

- Limitations of a single point of view
 - SEP observations mostly from along the Sun-Earth line
 - Can only determine where the solar source region is (often front side)
 - CME plane of sky speed
 - Not accurate for 'halo' CMEs
- Multiple longitude views
 - SEP characteristics

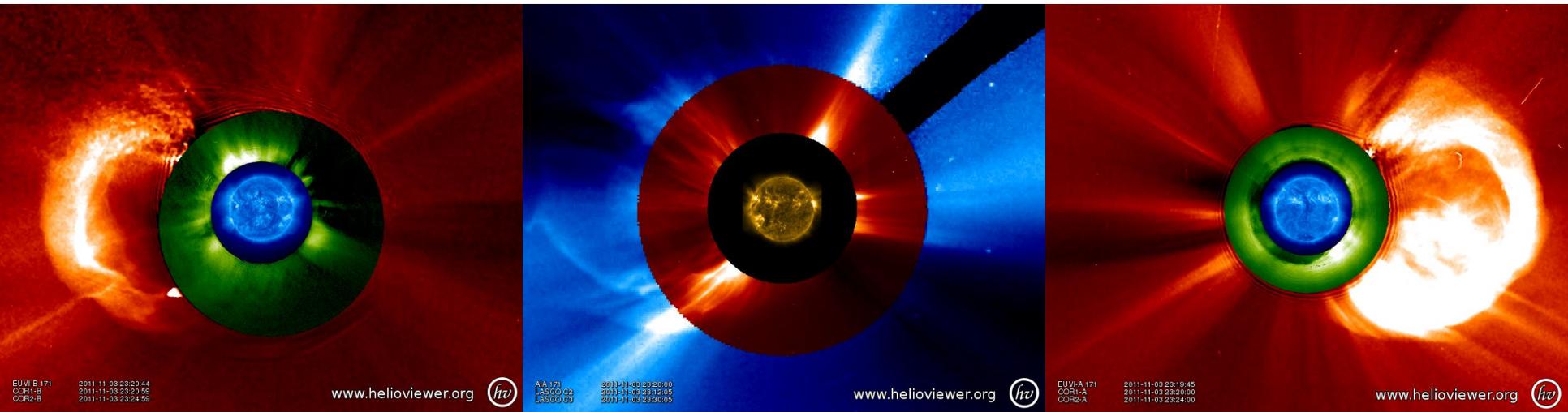


Expanding View

STEREO-B

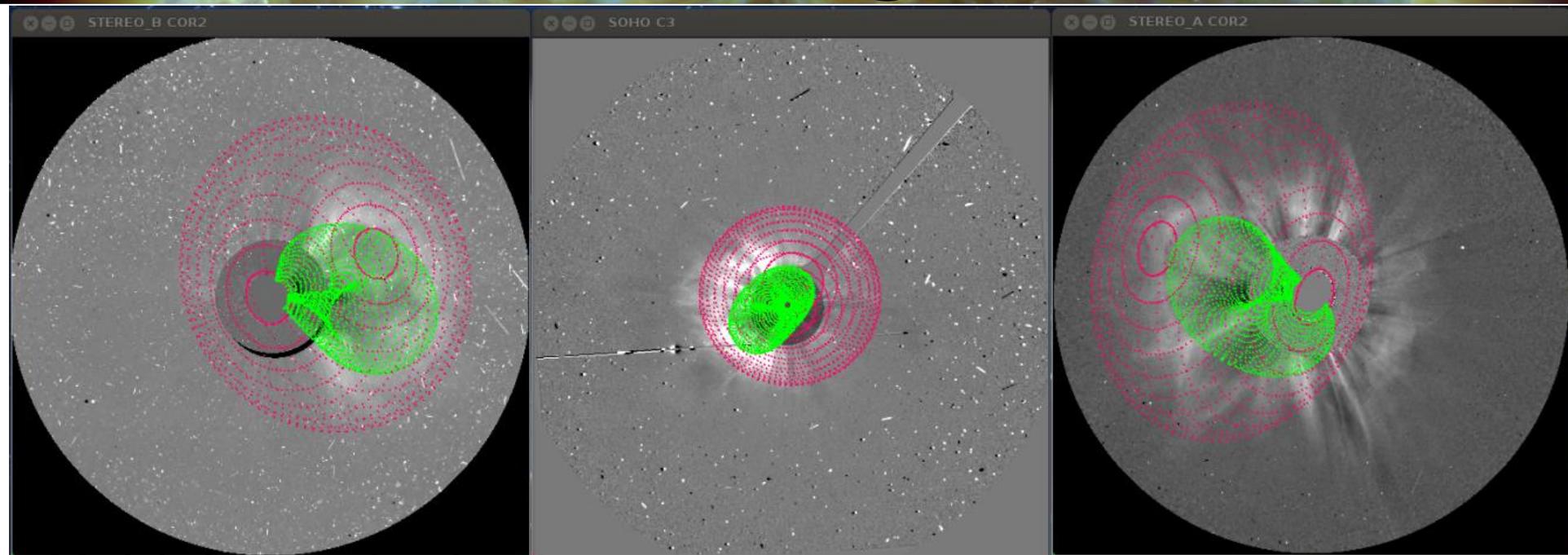
SOHO/SDO

STEREO-A



- Multiple longitude views
 - SEP characteristics
 - 3D reconstruction of CMEs

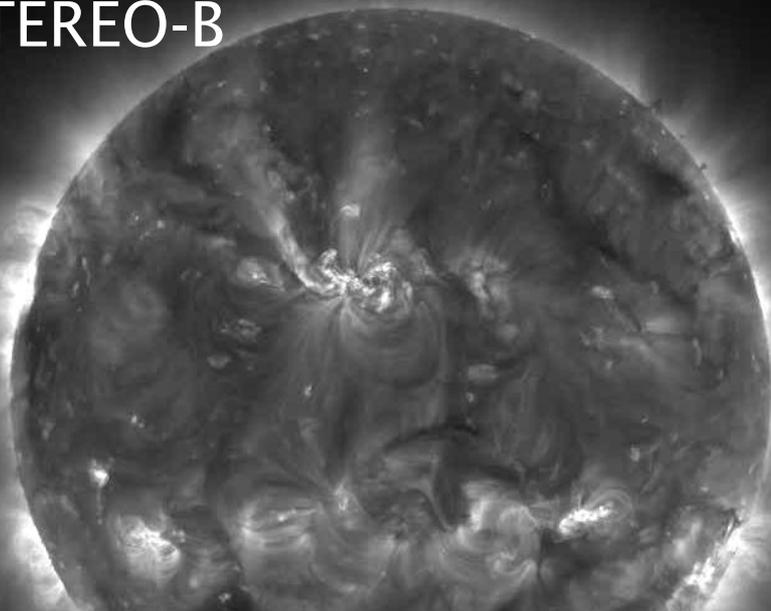
Expanding View



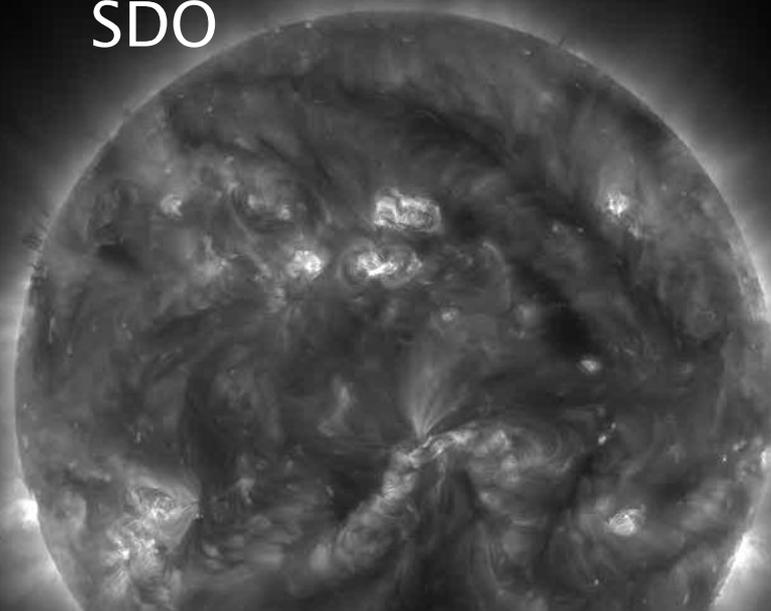
- Multiple longitude views
 - SEP characteristics
 - 3D reconstruction of CMEs

Expanding View

STEREO-B



SDO

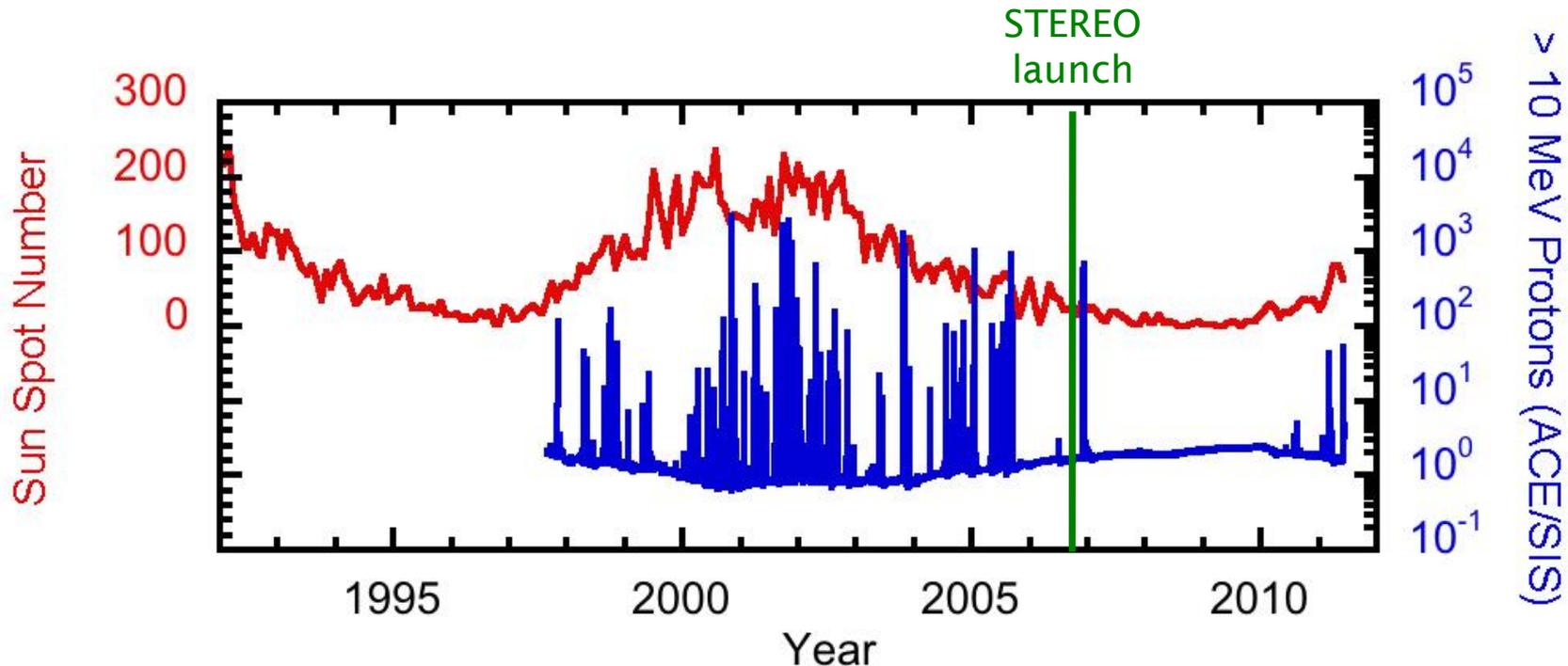


- Multiple longitude views
 - SEP characteristics
 - 3D reconstruction of CMEs

- Backside sources can be found

Solar Vacation

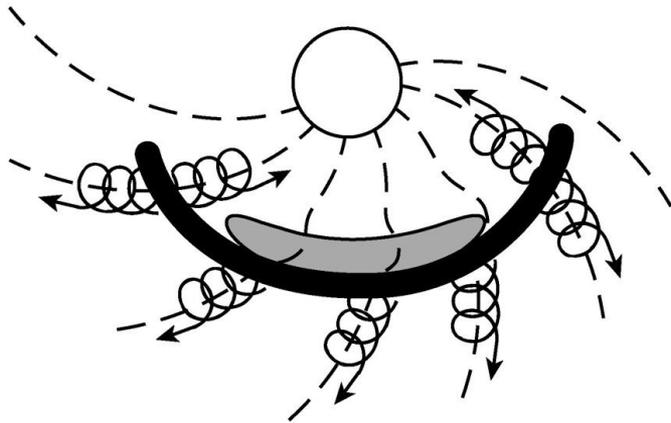
- STEREO launches into the quietest solar minimum in decades



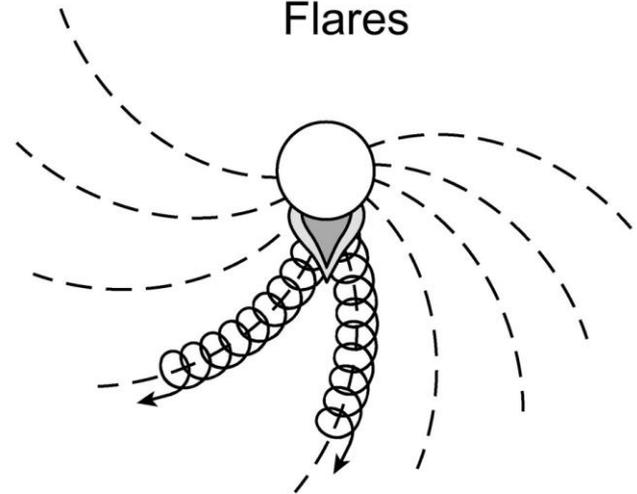
Two Flavors of SEPs

- CME-drive shock acceleration
 - ‘nominal’ composition (\neq SW)
 - Broad distribution
 - Evolving conditions
- Flare Acceleration
 - ^3He -rich, Fe-rich
 - Narrow populated area
 - Impulsive injection

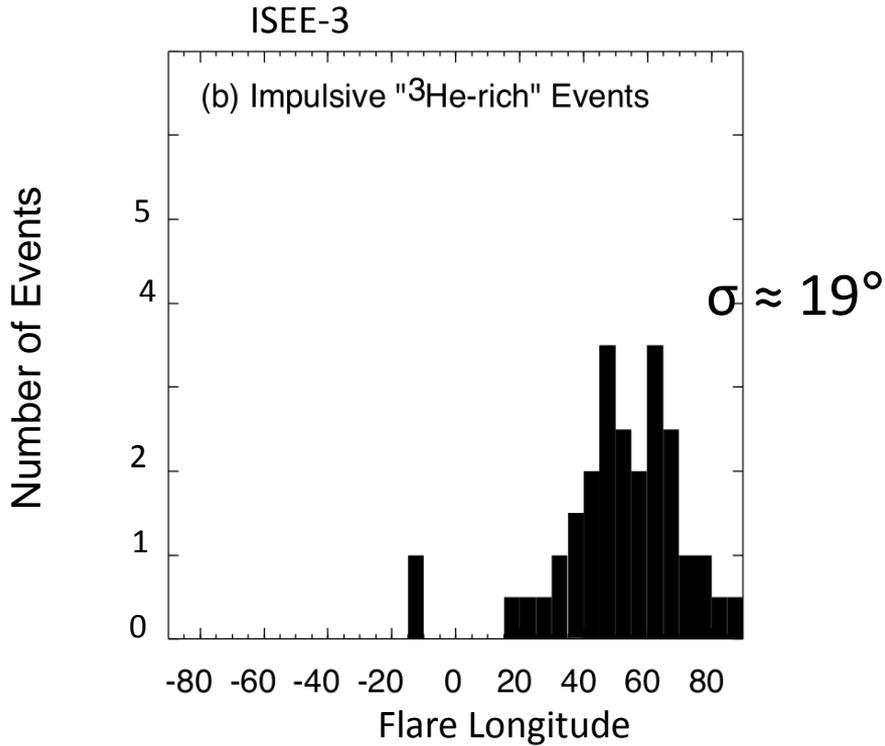
CME Shocks



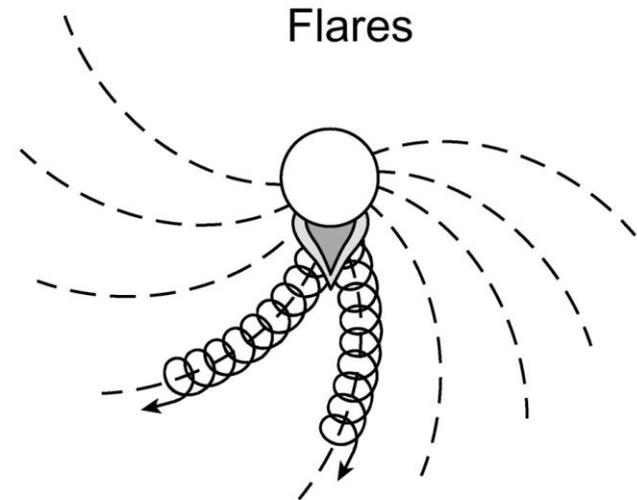
Flares



Two Flavors of SEPs

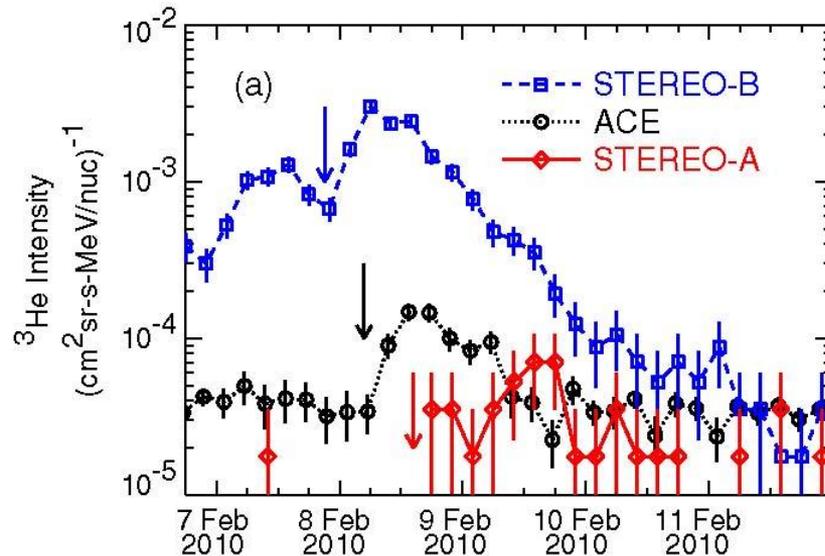
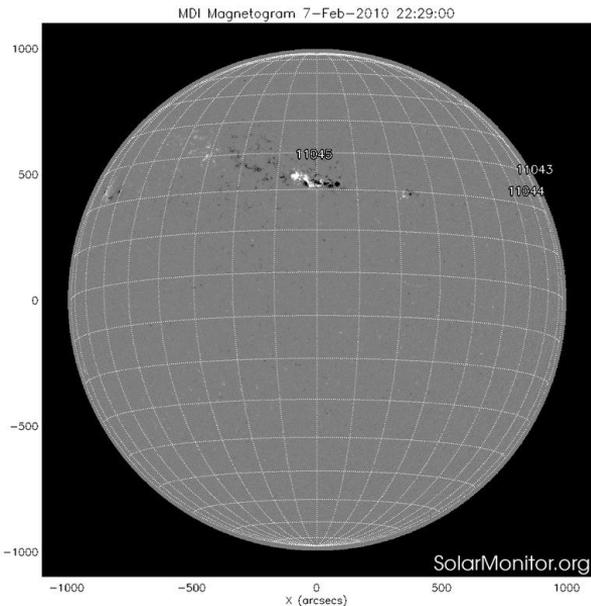


- Flare Acceleration
 - ^3He -rich, Fe-rich
 - Narrow populated area
 - Impulsive injection



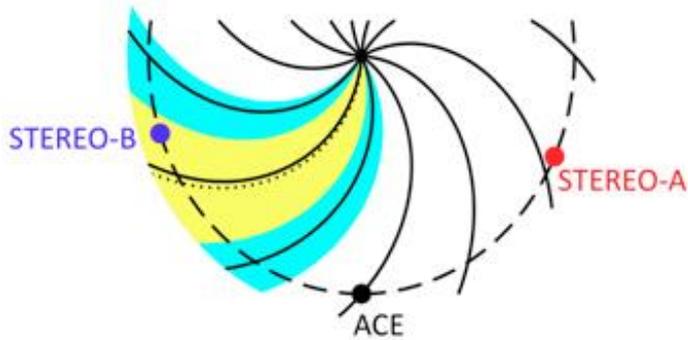
^3He -rich Events

- Some advantages to quiet conditions
 - Source regions easy to identify
 - ^3He -rich (impulsive) events seen by multiple s/c

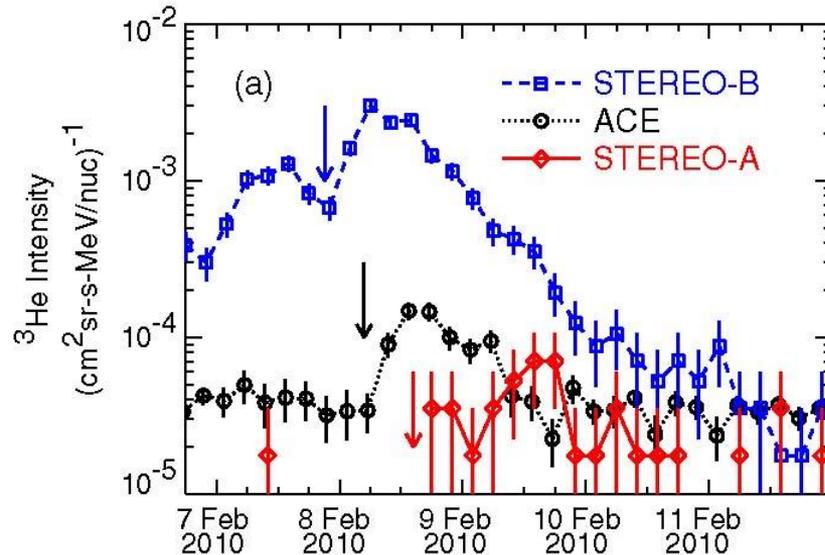


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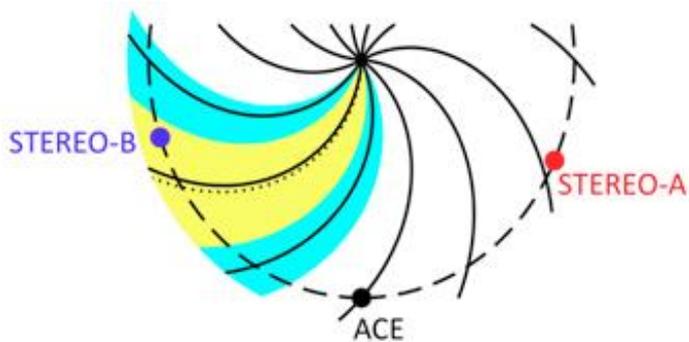


Spacecraft were 136°
apart!

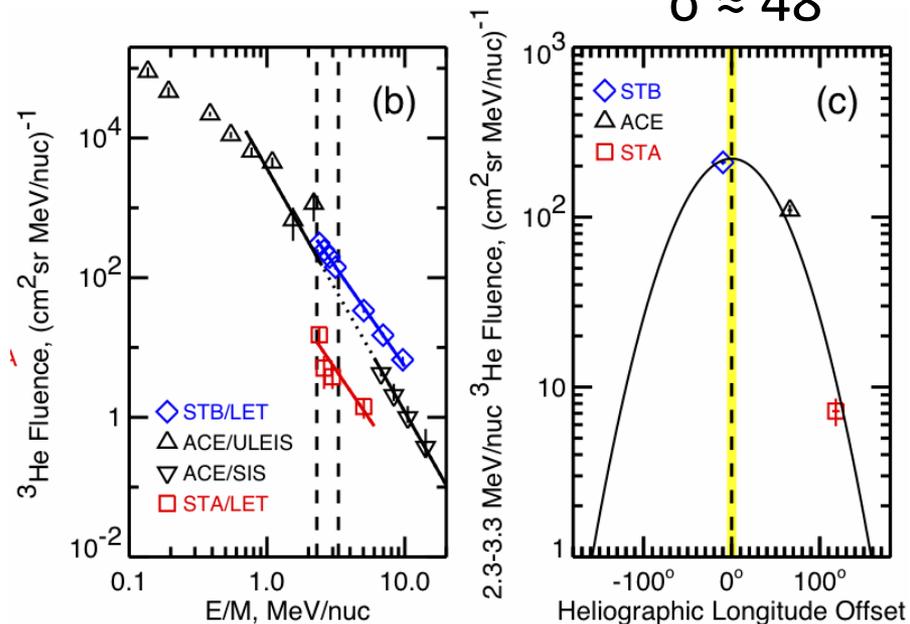


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Spacecraft were 136°
apart!



^3He -rich Events

- 7 Feb 2010 event singular?
- Survey by Wiedenbeck et al. 2011
 - Quiet conditions 2007-2010
 - Events $>60^\circ$ fairly common
- Are all ^3He -rich events wide?
 - Survey of single s/c events

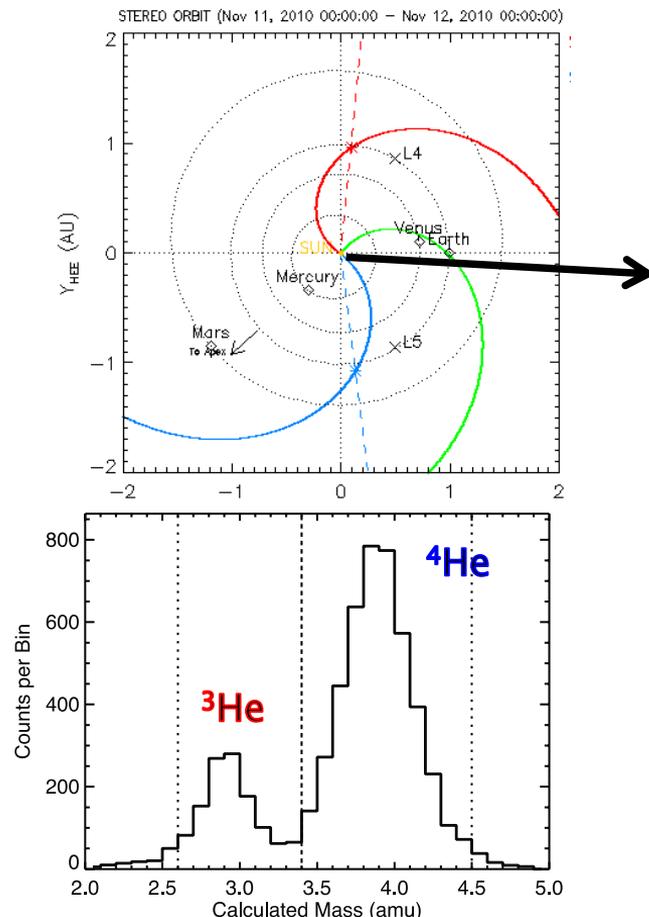
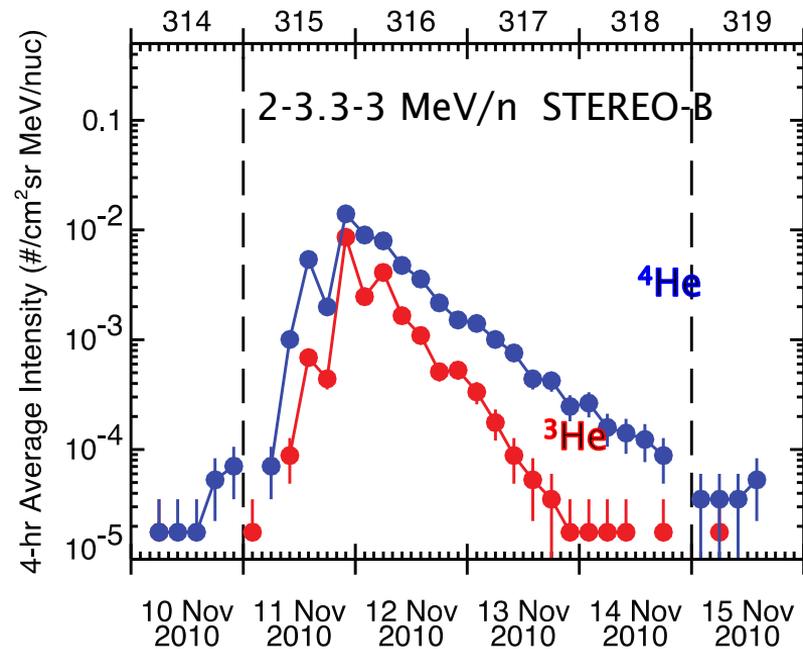
Table 1: ^3He -rich Events Detected by STEREO

Time Interval	STEREO A–B Separation	Events Detected ^a		
		1 S/C	2 S/C	3 S/C
2007 Jan–Jun	$0^\circ - 16^\circ$	0	0	1
2007 Jul–Dec	$16^\circ - 44^\circ$	0	0	0
2008 Jan–Jun	$44^\circ - 59^\circ$	0	0	0
2008 Jul–Dec	$59^\circ - 88^\circ$	1	1	0
2009 Jan–Jun	$88^\circ - 102^\circ$	0	1	0
2009 Jul–Dec	$102^\circ - 132^\circ$	2	1	0
2010 Jan–Jun	$132^\circ - 145^\circ$	2	2	2
2010 Jul–Dec	$145^\circ - 175^\circ$	1	6	0

^a 1 S/C: one STEREO only; 2 S/C: one STEREO+ACE

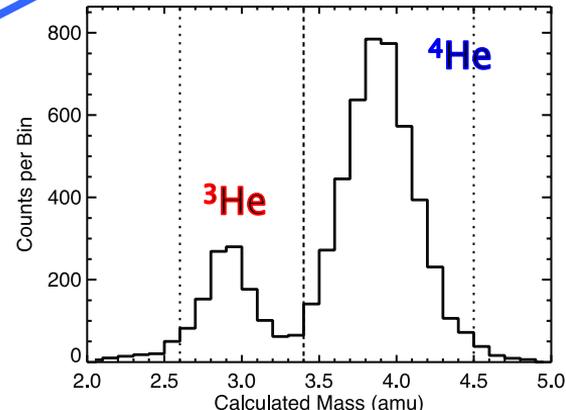
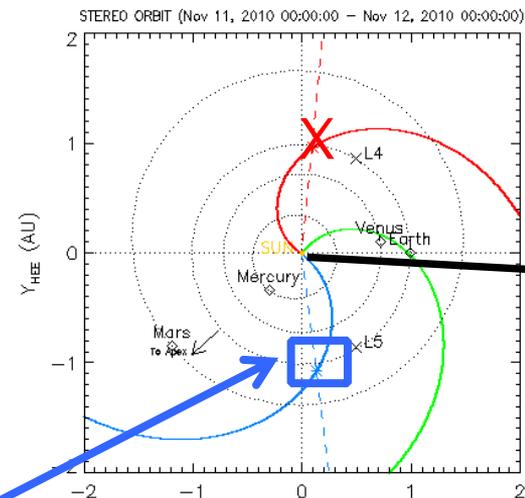
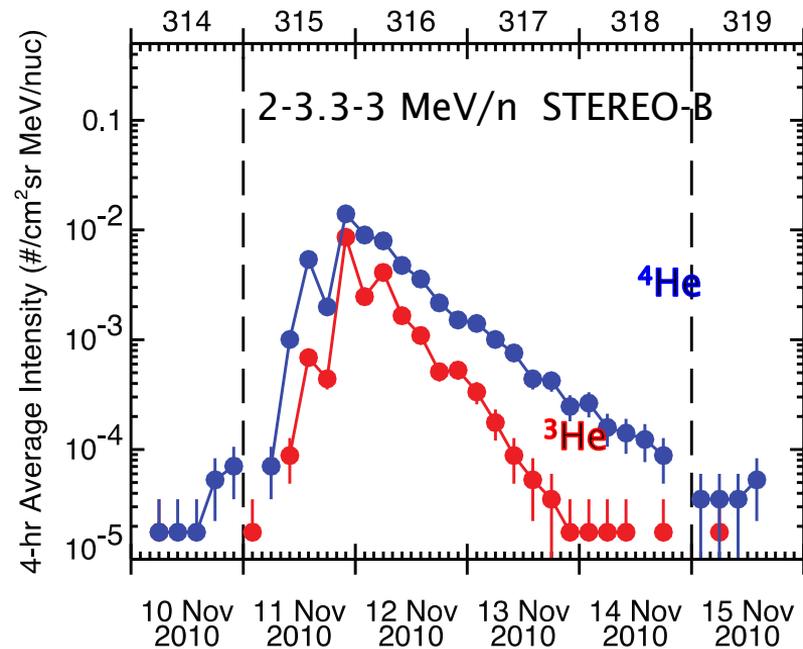
Single S/C ^3He -rich Events

- Picked events of sufficient size



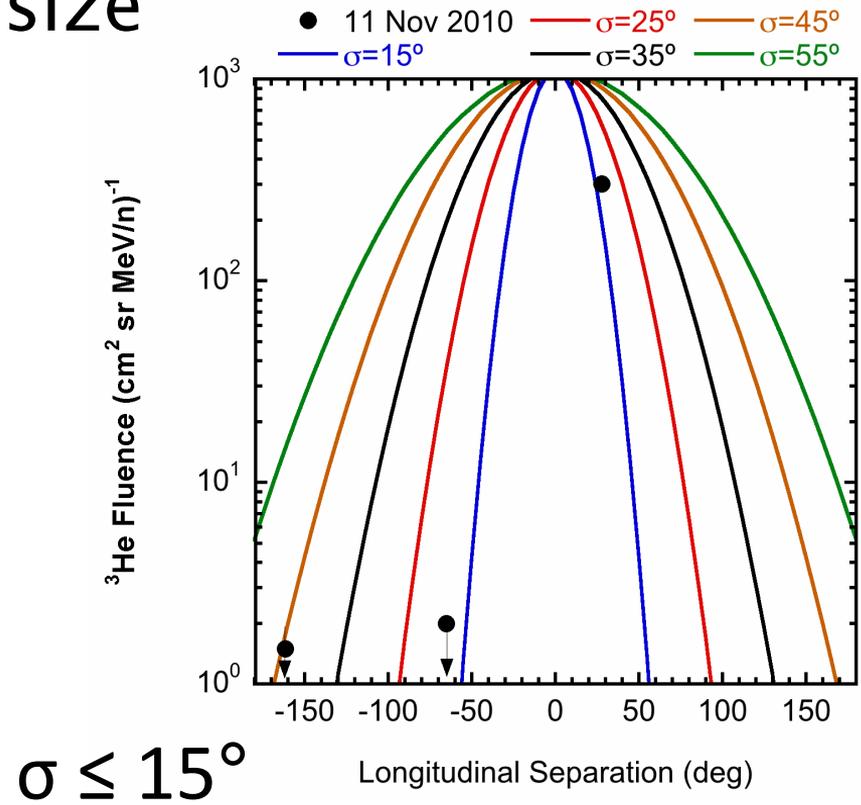
Single S/C ^3He -rich Events

- Picked events of sufficient size
- Seen by single STEREO

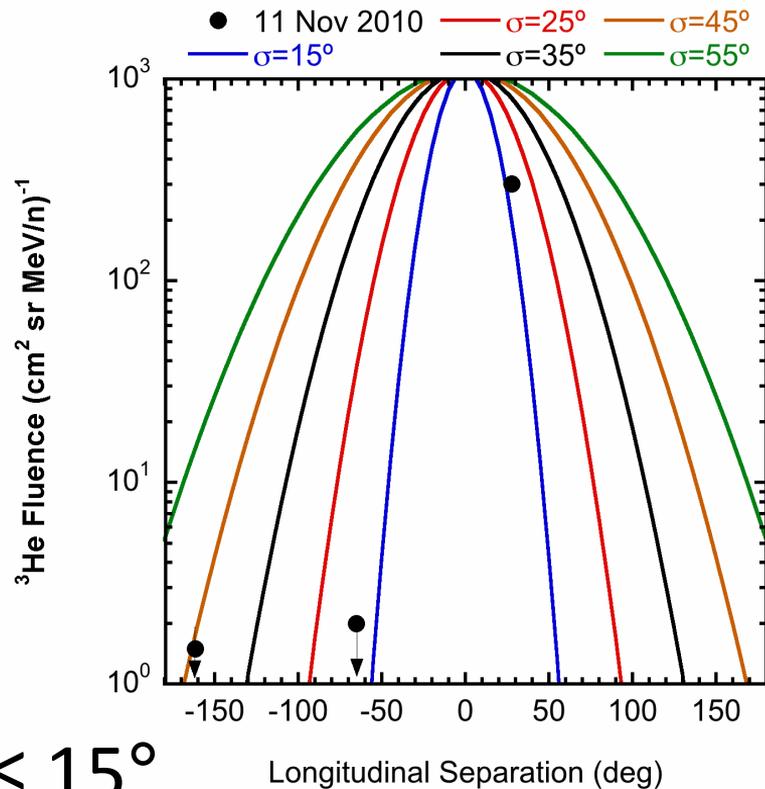
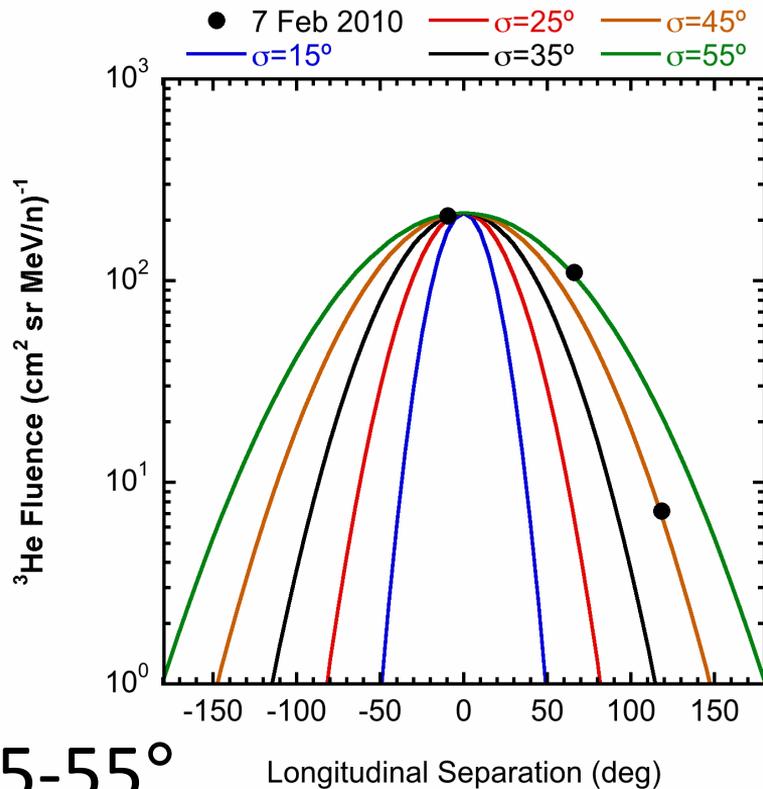


Single S/C Events

- Picked events of sufficient size
- Seen by single STEREO
- Center Gaussian on flare location



Single S/C Events



Possible Explanations

- Solar
 - Sympathetic flaring/multiple sources
 - Field line spreading
 - Complex reconnection (near Sun)
 - Coronal transport
- Interplanetary
 - Field line meandering
 - Co-rotation
 - Cross-field diffusion

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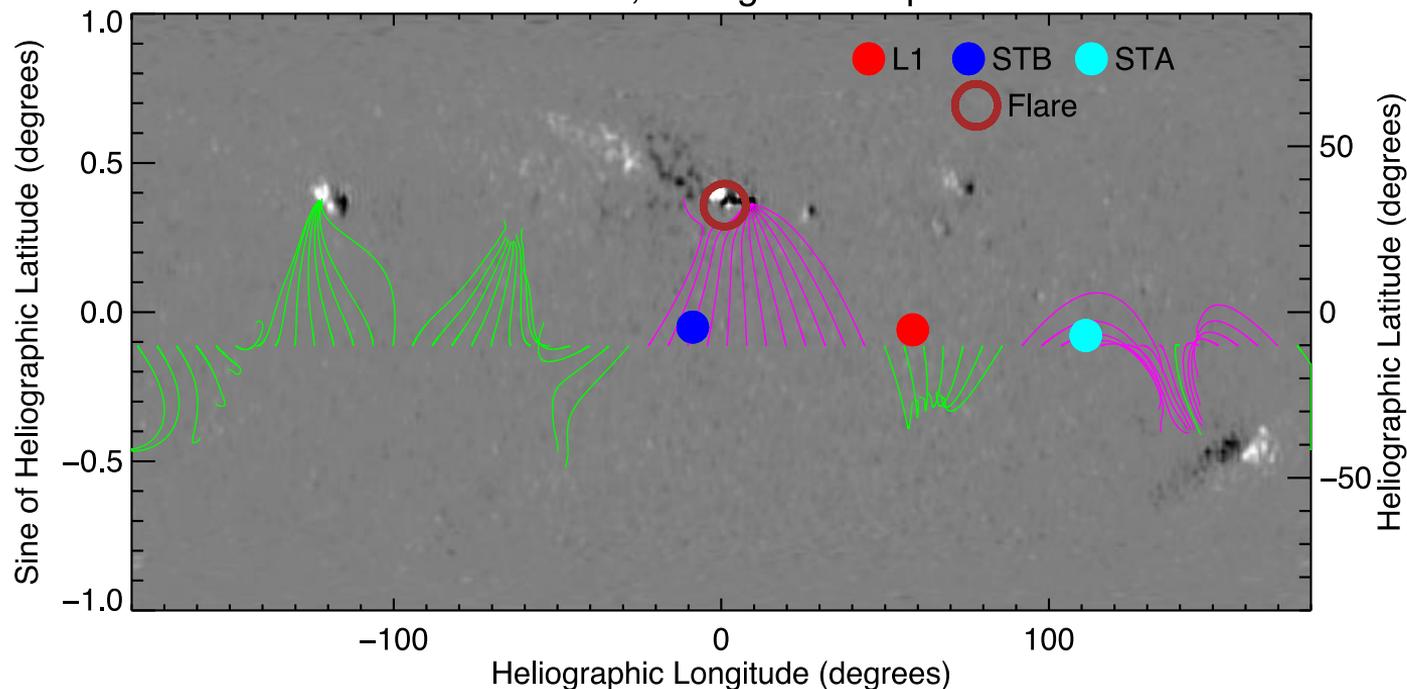
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Field Line Spreading

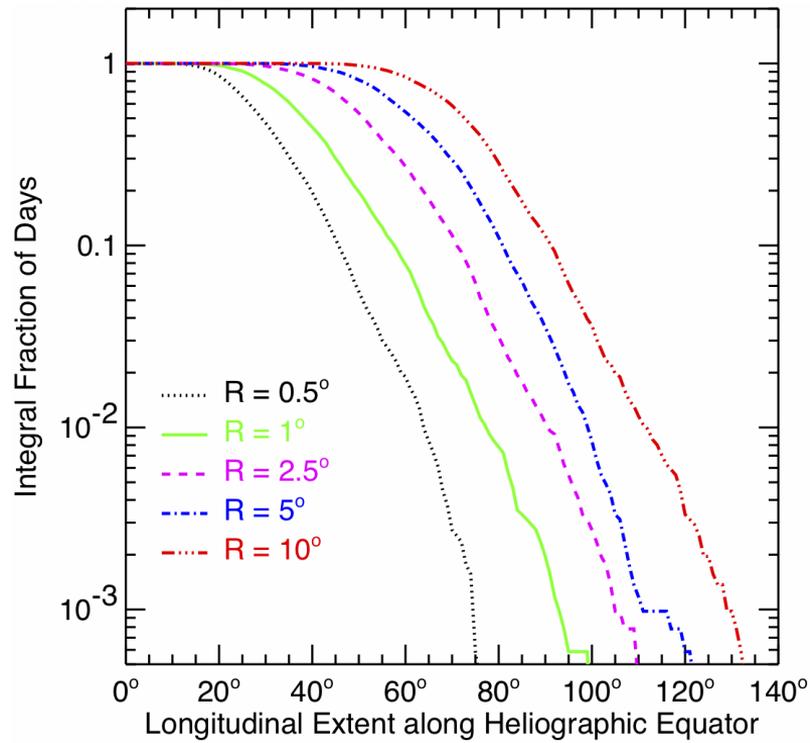
- Magnetograms + potential field calculations
- PFSS model shows $\sim 60^\circ$ spread at 2.5 Rs

PFSS for 8-Feb-2010 04:10:00; Magnetic map at 8-Feb-2010 12:04:00



Field Line Spreading

- Magnetograms + potential field calculations
- PFSS model shows $\sim 60^\circ$ spread at 2.5 Rs
- 12 years of maps rarely get $> 120^\circ$ spread



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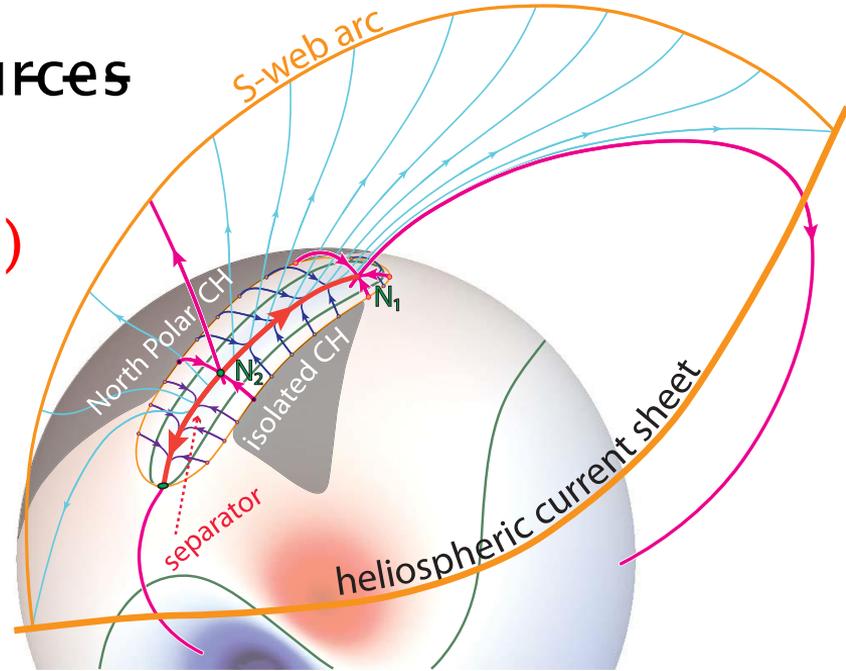
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Linker et al. 2011

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Possible Explanations

- Solar

- ~~Sympathetic flaring/multiple sources~~
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- ~~Field line meandering (10°)~~
- Co-rotation
- Cross-field diffusion

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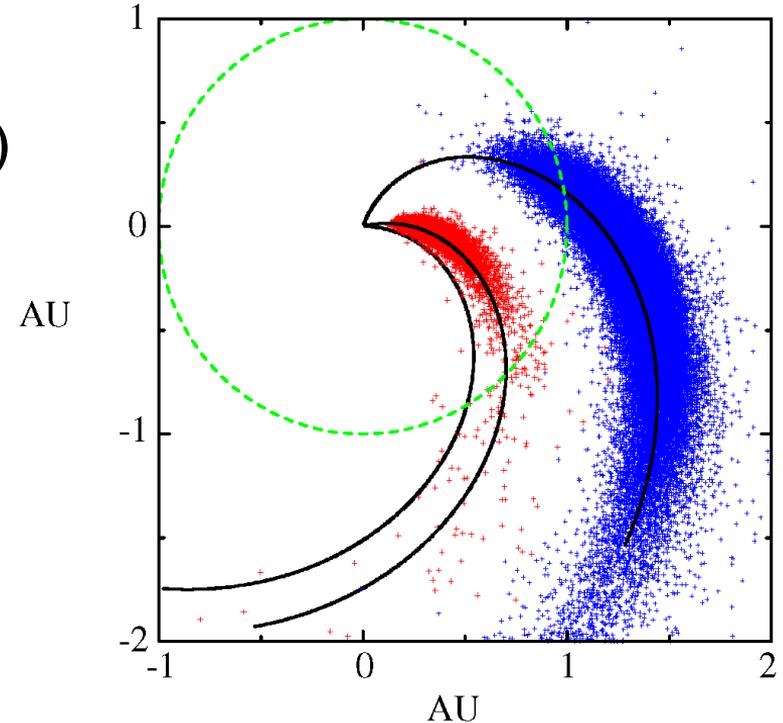
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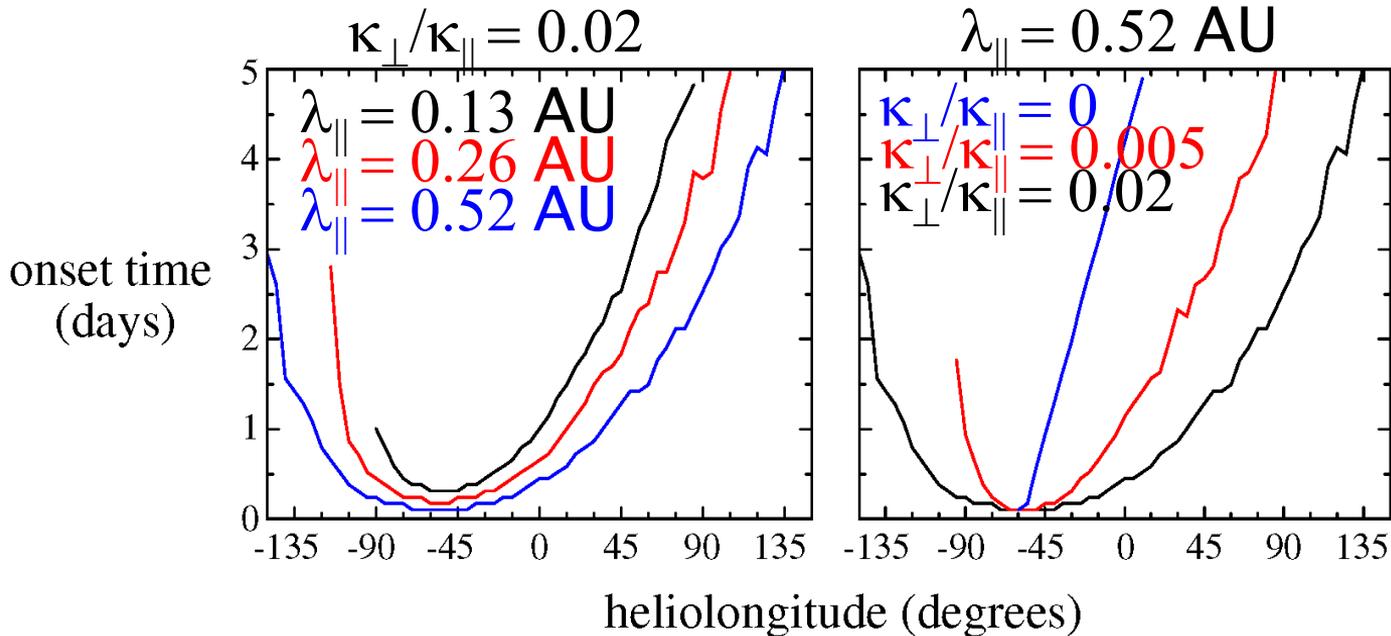
- ~~Field line meandering (10°)~~
- **Co-rotation**
- Cross-field diffusion

Giacalone & Jokipii 2012



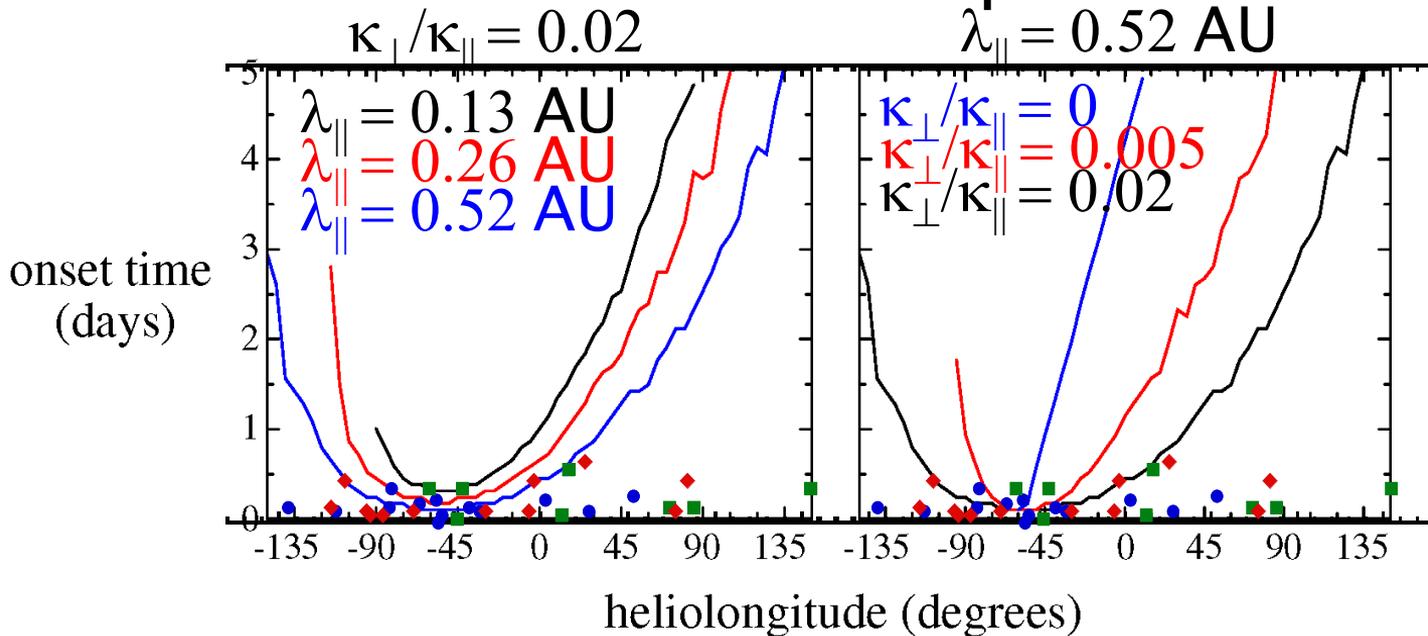
Corotation Effects

- Solving Parker diffusion equation
 - Onset delays at each s/c depend on both λ_{\parallel} and $\kappa_{\perp}/\kappa_{\parallel}$



Corotation Effects

- Solving Parker diffusion equation
 - Onset delays at each s/c depend on both λ_{\parallel} and $\kappa_{\perp}/\kappa_{\parallel}$
- Observations show less dependence on longitude



Possible Explanations

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- ~~Sympathetic flaring/multiple sources~~
- ~~Field line spreading~~
- Complex reconnection (near Sun)
- Coronal transport

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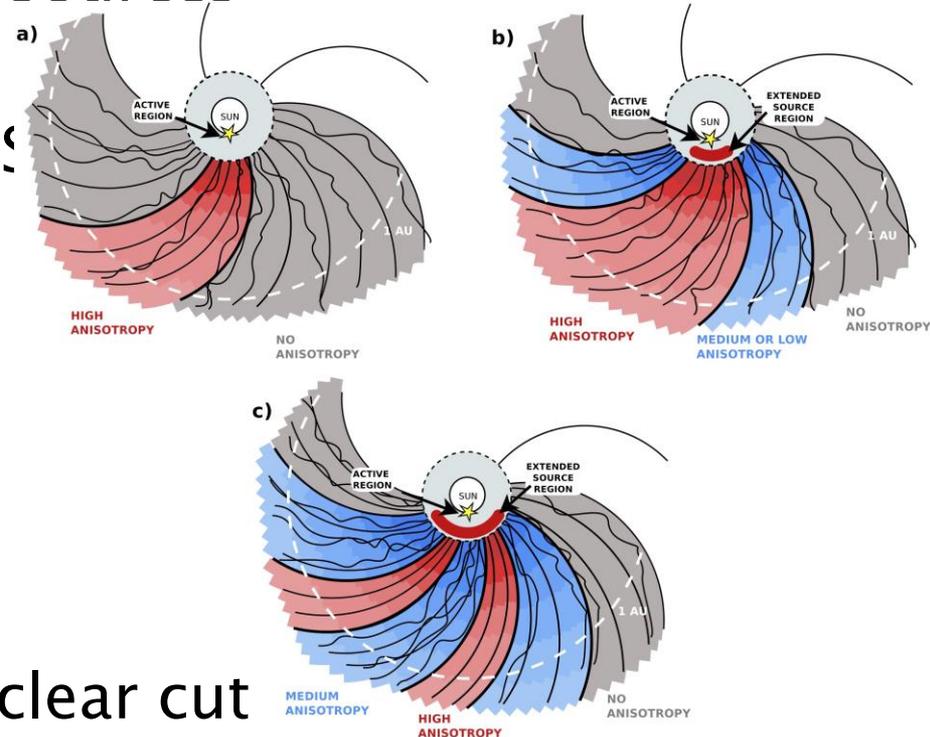
• **Coronal transport**

• Interplanetary

- ~~Field line meandering (10°)~~
- ~~Co-rotation~~
- **Cross-field diffusion**

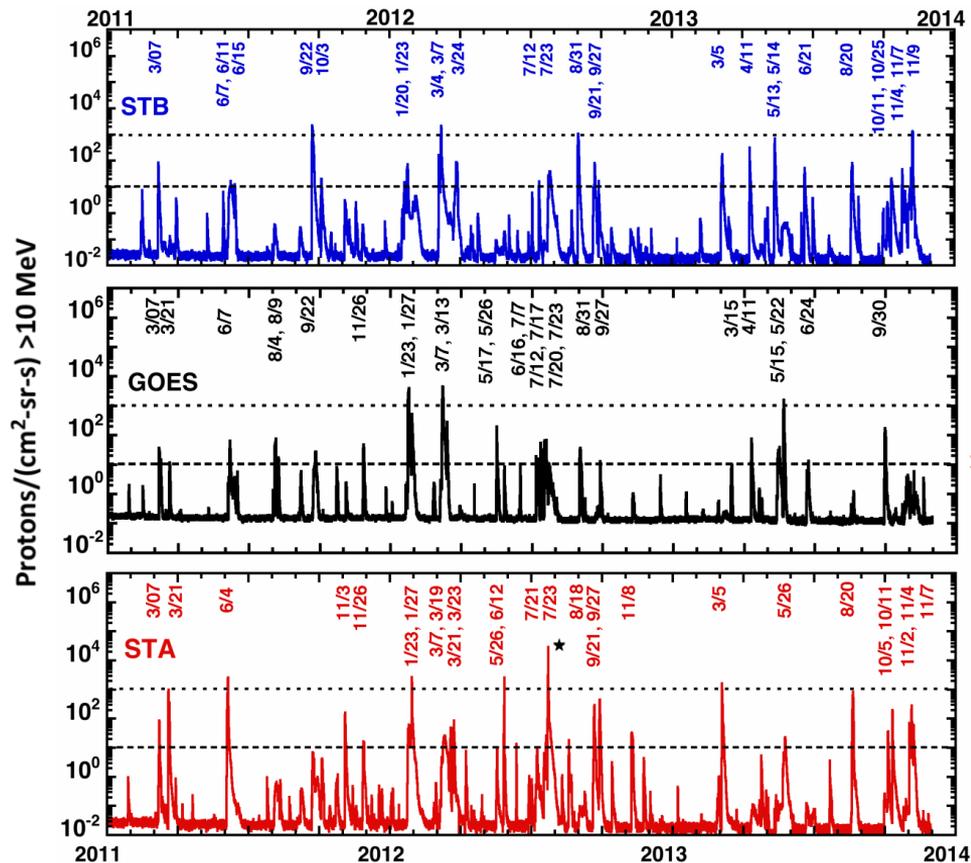
Possibly both – not clear cut

Dresing et al. 2014



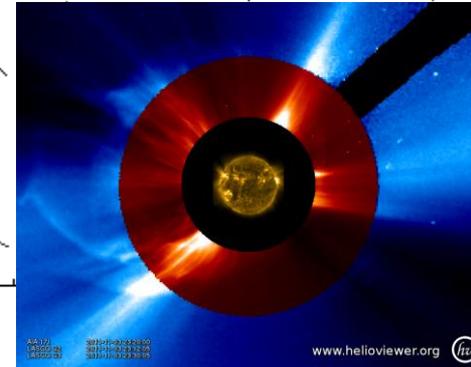
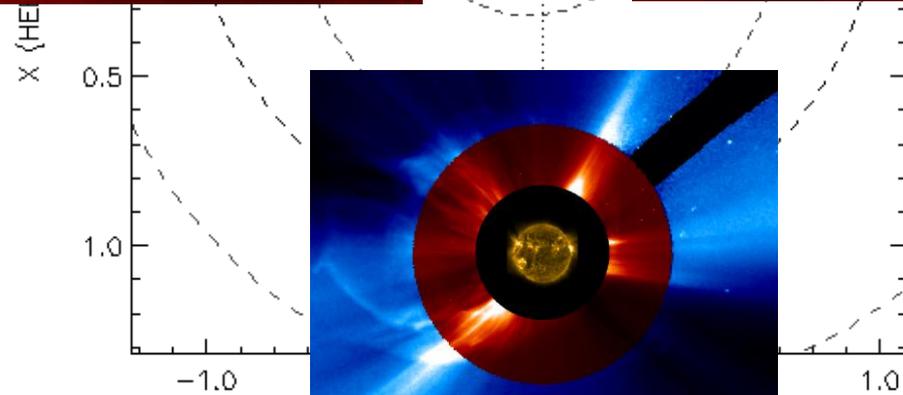
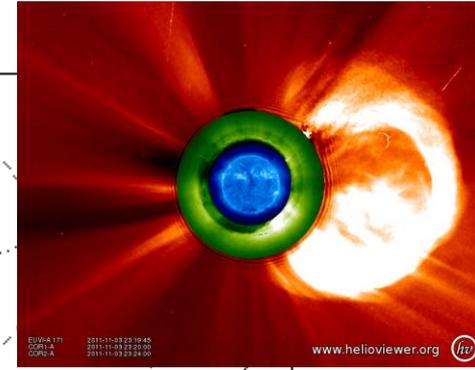
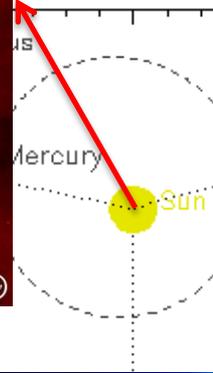
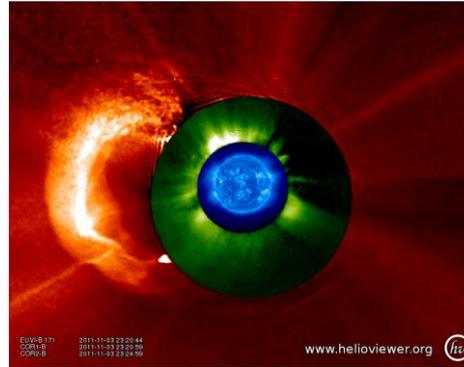
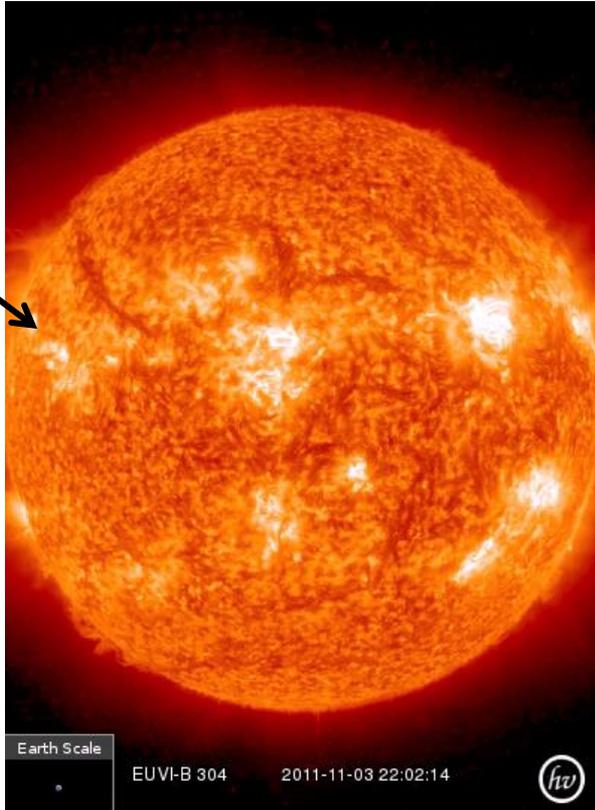
Large SEP Events

- SEP activity increases 2011
- Many events are multi-s/c
 - Source regions clearly identified
 - Backside source regions show some surprises



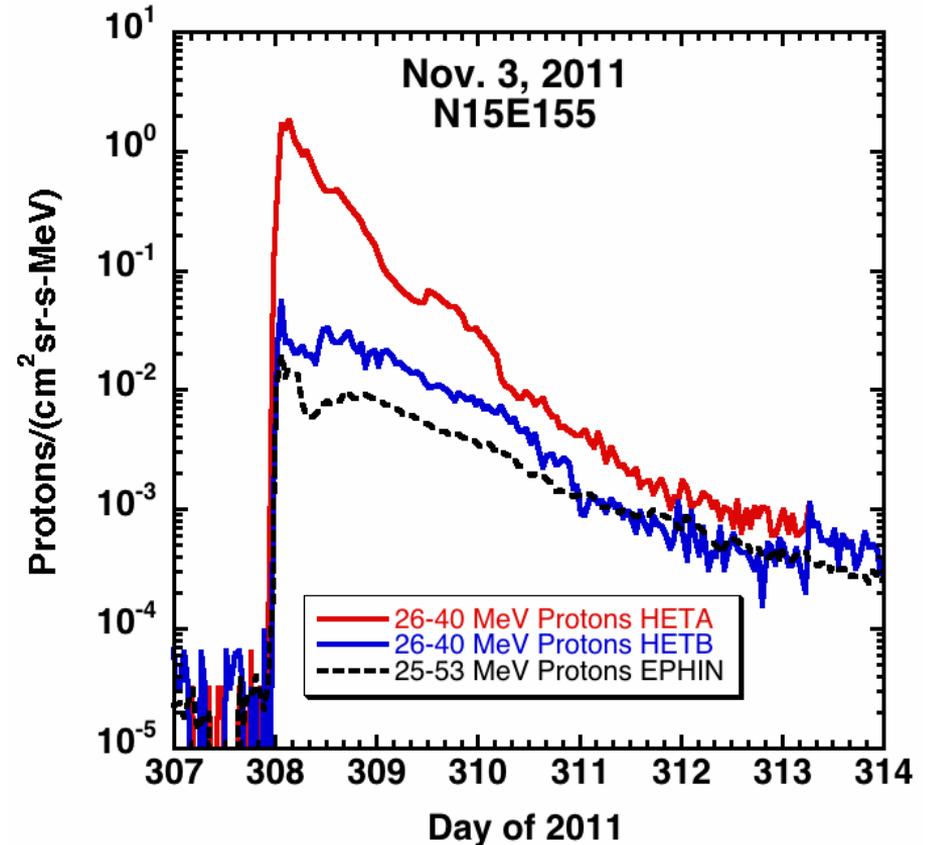
Backside Events

- 3 Nov 2011 event



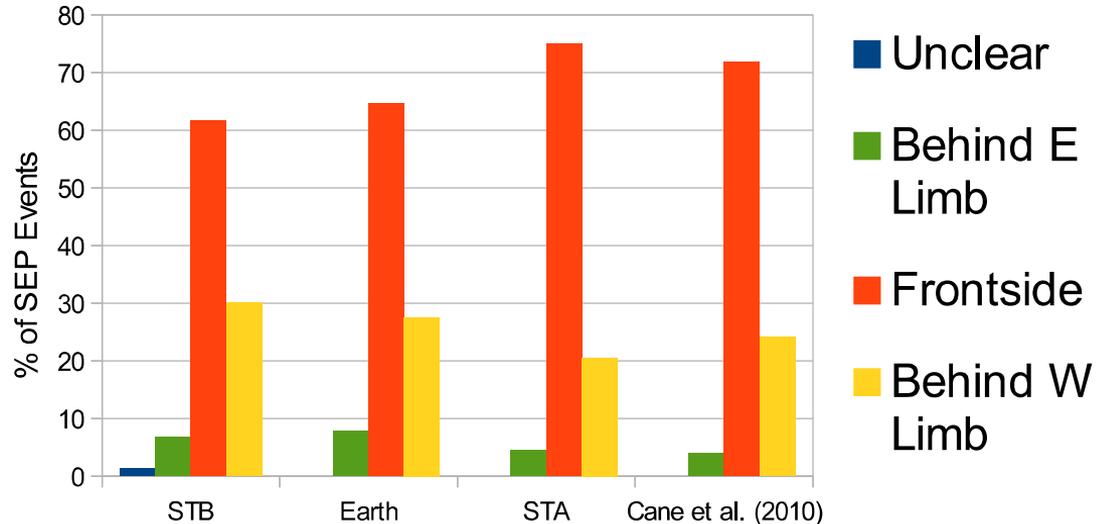
Backside Events

- 3 Nov 2011 event
- Fast 25 MeV H⁺ onsets at all 3 s/c
- Backside ≠ Slow rise



Backside Events

- 3 Nov 2011 event
- Fast 25 MeV H⁺ onsets at all 3 s/c
- Backside \neq Slow rise
- 1/3 of events have backside sources

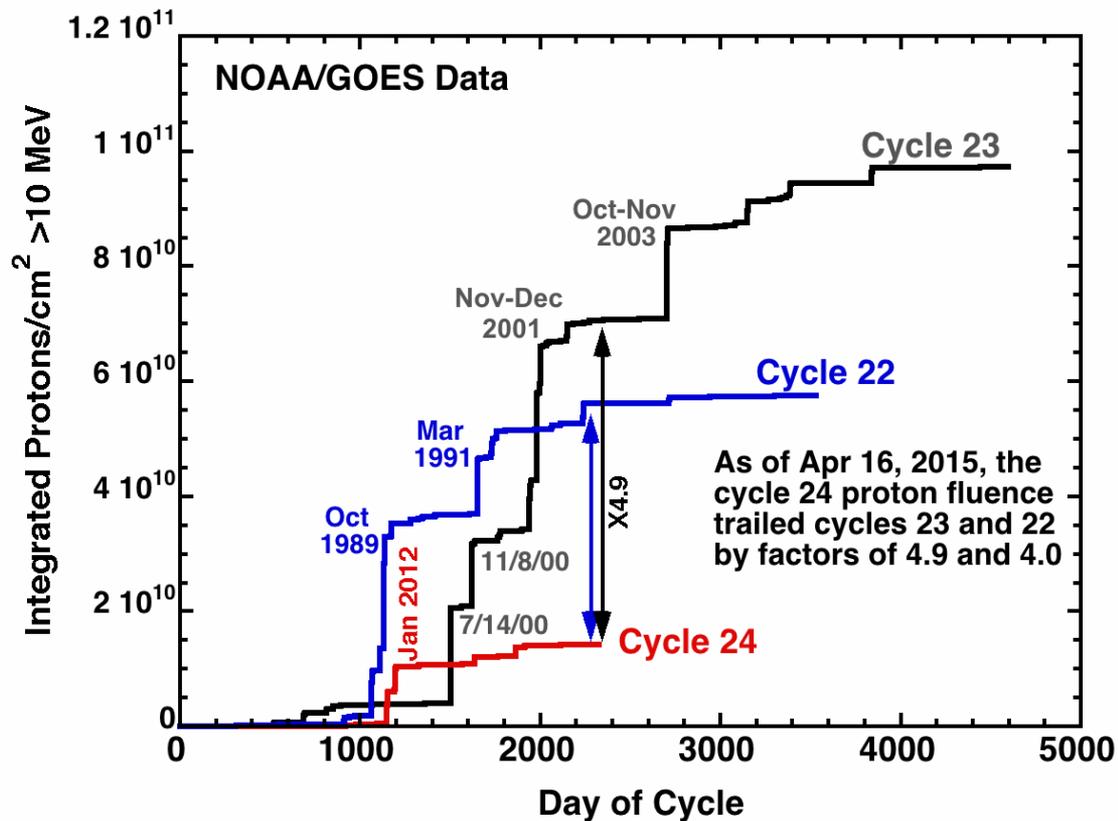


Need to understand the fast transport & conditions that favor it

Richardson et al. 2014

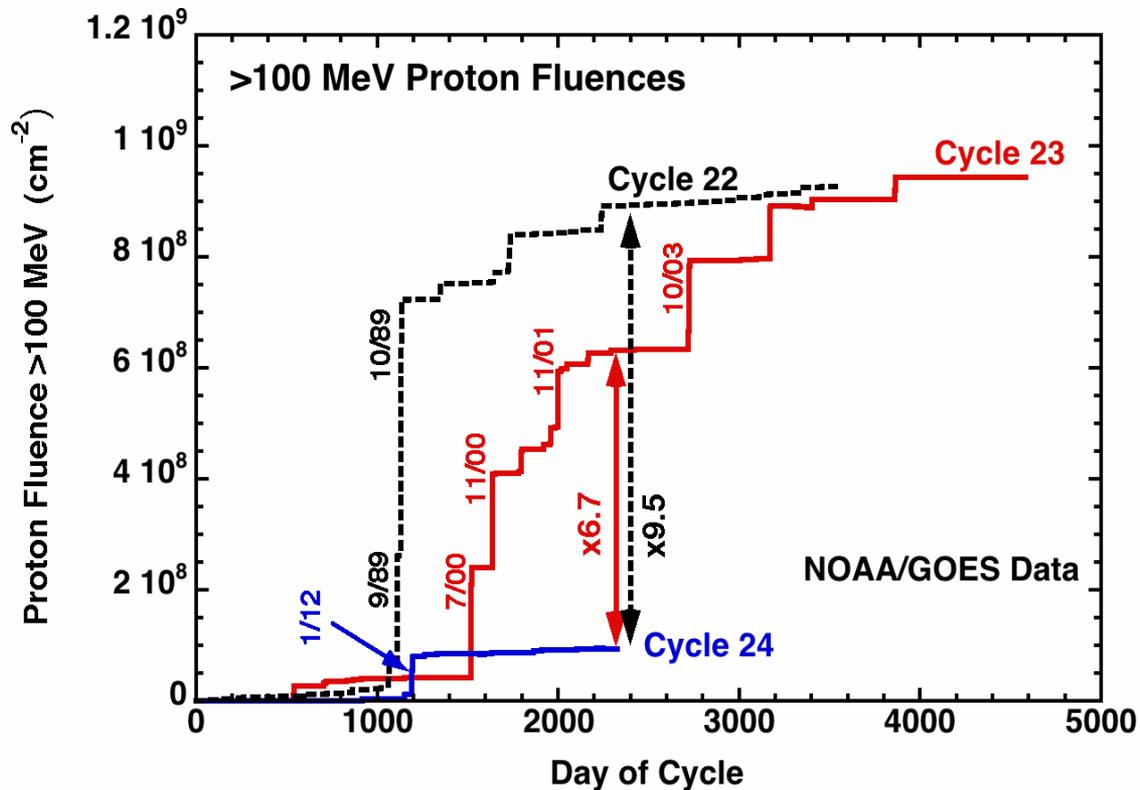
Temporal Changes

- Cycle 24 is different
 - SEP production is down



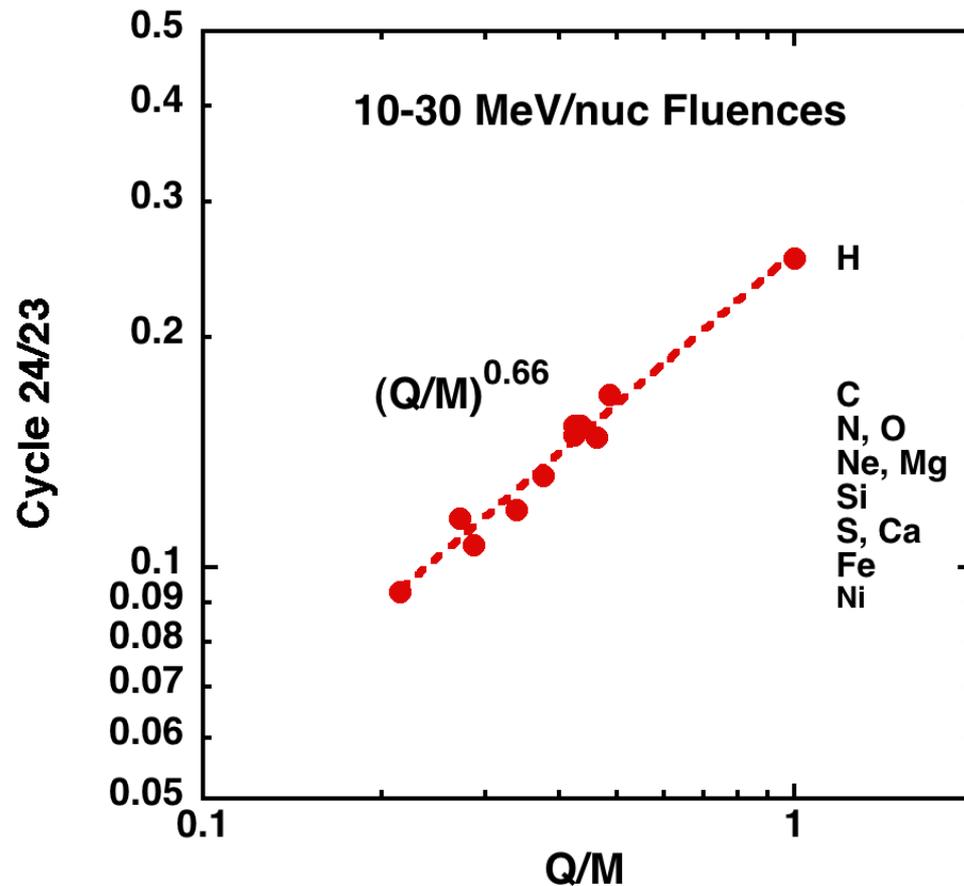
Temporal Changes

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 - High energy SEP production is down more



Temporal Changes

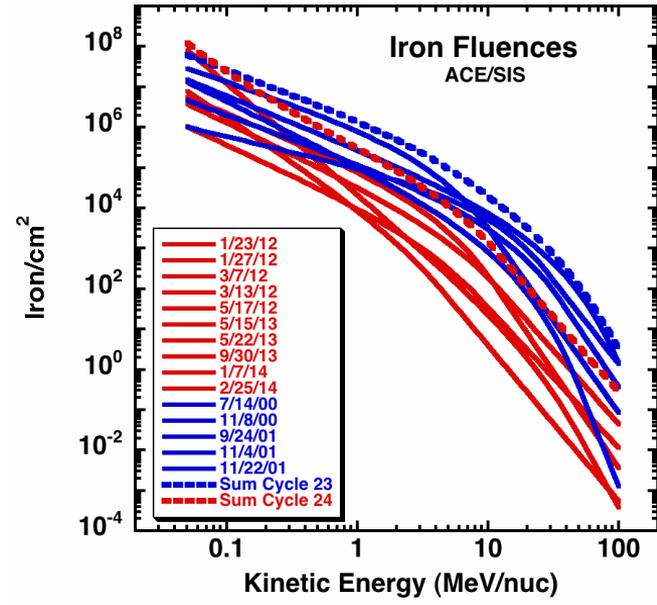
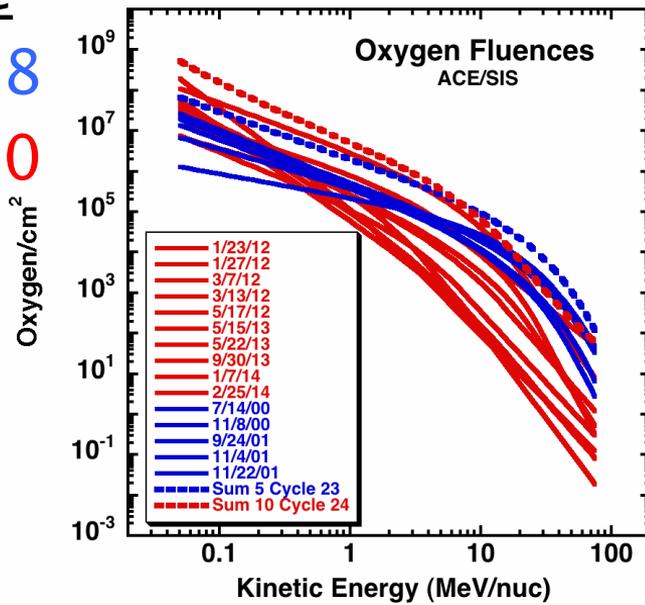
- Cycle 24 is different
 - SEP production is down
 - High energy SEP production is down more
 - 10-30 MeV/n heavy ions are further reduced



Weak Cycle 24

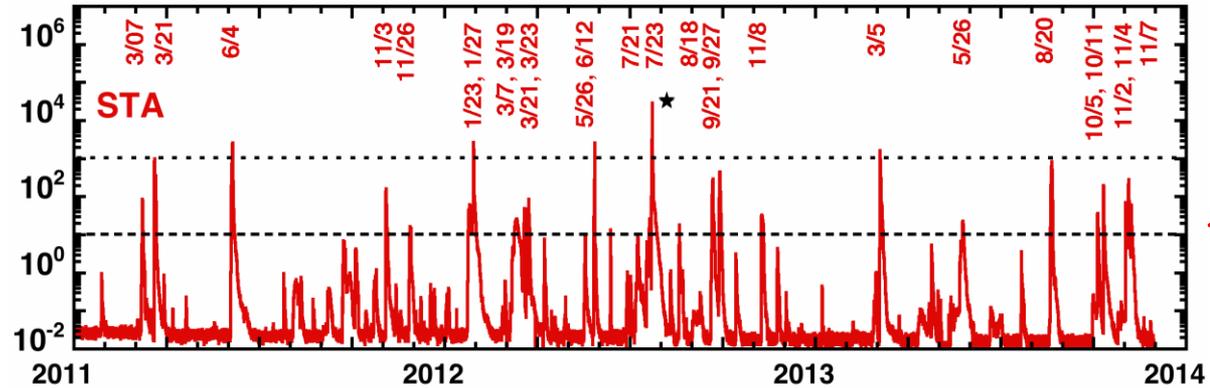
- O and Fe spectra fits for the 5 largest events of cycle 23 (first 5.8 yrs) & 10 largest cycle 24 events
- Break energies are lower in cycle 24

Cycle	O	Fe
23	24.3	4.8
24	5.3	2.0



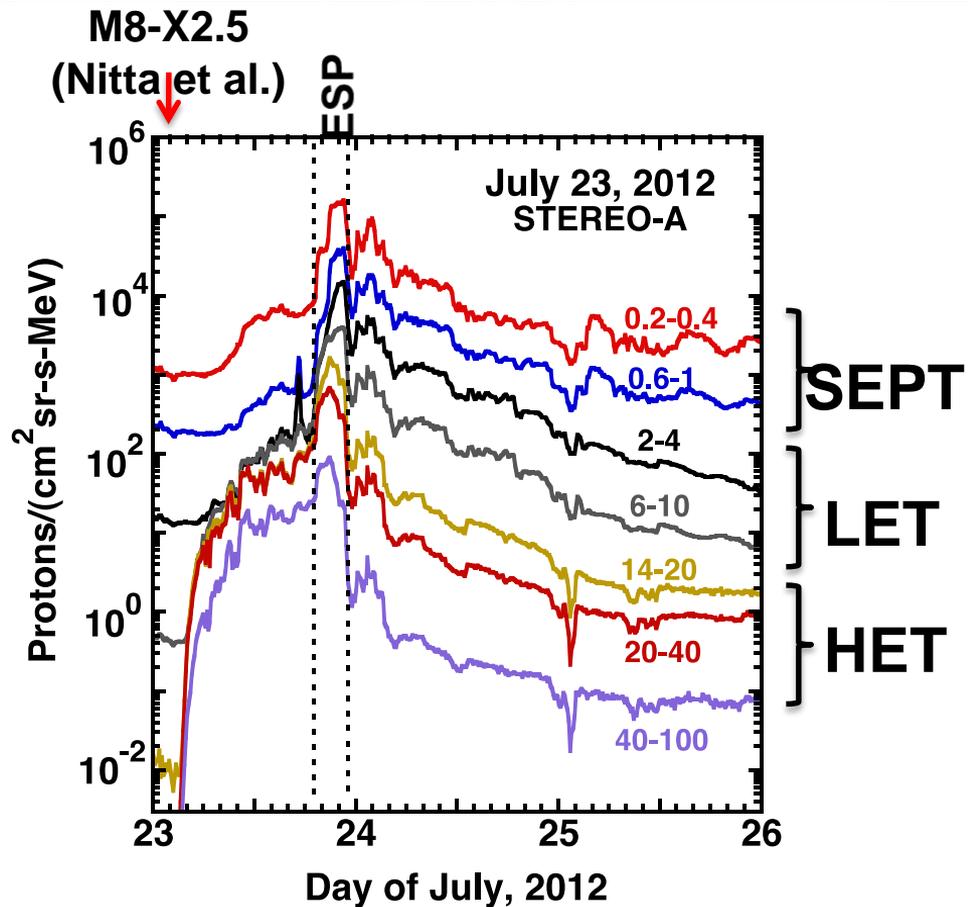
Weak \neq Boring

- 23 July 2012
 - STEREO-A saw the largest event of cycle 24



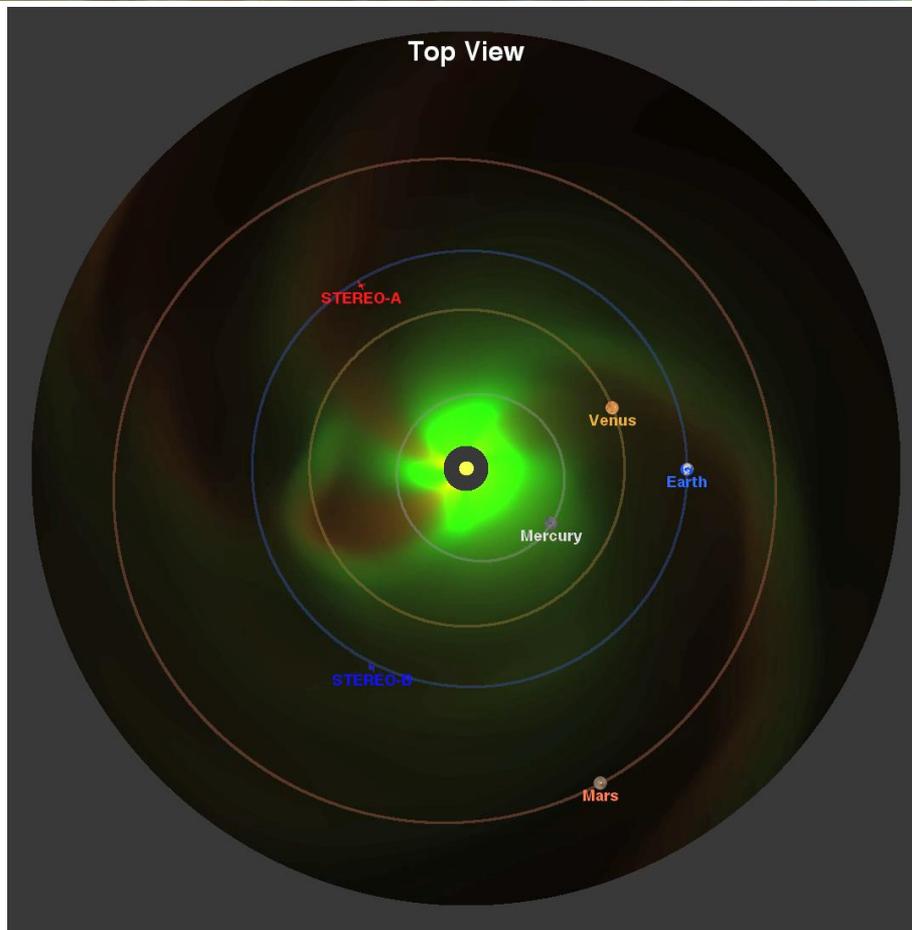
Weak \neq Boring

- 23 July 2012
 - STEREO-A saw the largest event of cycle 24
 - B field reaches 109 nT
 - V reaches ~ 2250 km/s



Weak \neq Boring

- 23 July 2012
 - STEREO-A saw the largest event of cycle 24
 - B field reaches 109 nT
 - V reaches ~ 2250 km/s
- Weak event at Earth
 - Just 'lucky'?
 - Possibly catastrophic geomagnetic storm



Weak ≠ Boring

• 23 July 2012

- STEREO-A saw the largest event of cycle 24
- B field reaches 109 nT
- V reaches ~2250 km/s
- Weak event at Earth
 - Just 'lucky'?
 - Possibly catastrophic geomagnetic storm
- Third largest event

NOAA Top 20 Solar Proton Events
GOES >10 MeV Protons: 1976-2013

Rank	Year	Month	Start	Intensity P/(cm ² sr-s)
1	1991	Mar	23/0820	43000
2	1989	Oct	19/1305	40000
3	2001	Nov	04/1705	31700
4	2003	Oct	28/1215	29500
5	2000	Jul	14/1045	24000
6	2001	Nov	22/2320	18900
7	2000	Nov	Aug-50	14800
8	2001	Sep	24/1215	12900
9	1994	Feb	20/0300	10000
10	1989	Aug	12/1600	9200
11	1989	Nov	30/1345	7300
12	2012	Mar	07/0510	6530
13	2012	Jan	23/0530	6310
14	2005	Jan	16/0210	5040
15	1992	May	09/1005	4600
16	1989	Sep	29/1205	4500
17	1989	Mar	08/1735	3500
18	2005	May	14/0525	3140
19	1991	Jun	04/0820	3000
20	1982	Jul	11/0700	2900

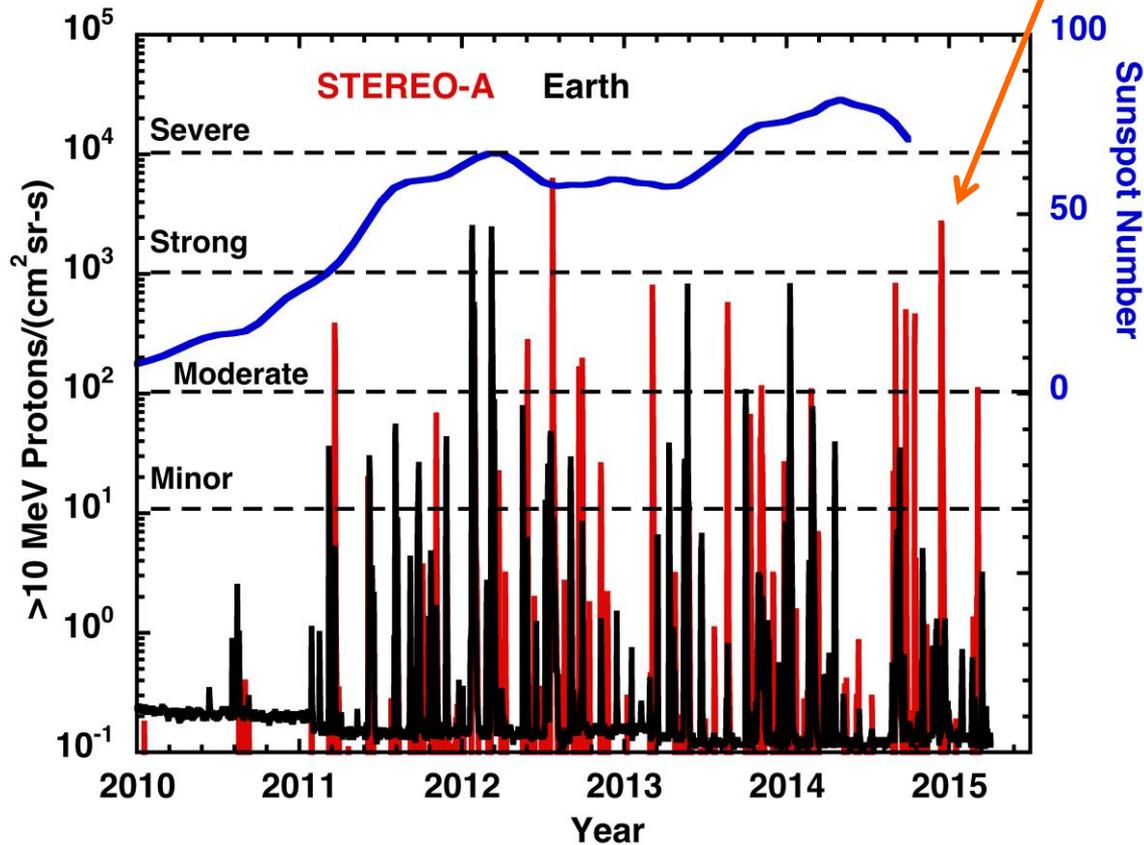
! 23 July 2012 =
35800 p/cm²sr-s

 Cycle 23

 Cycle 24

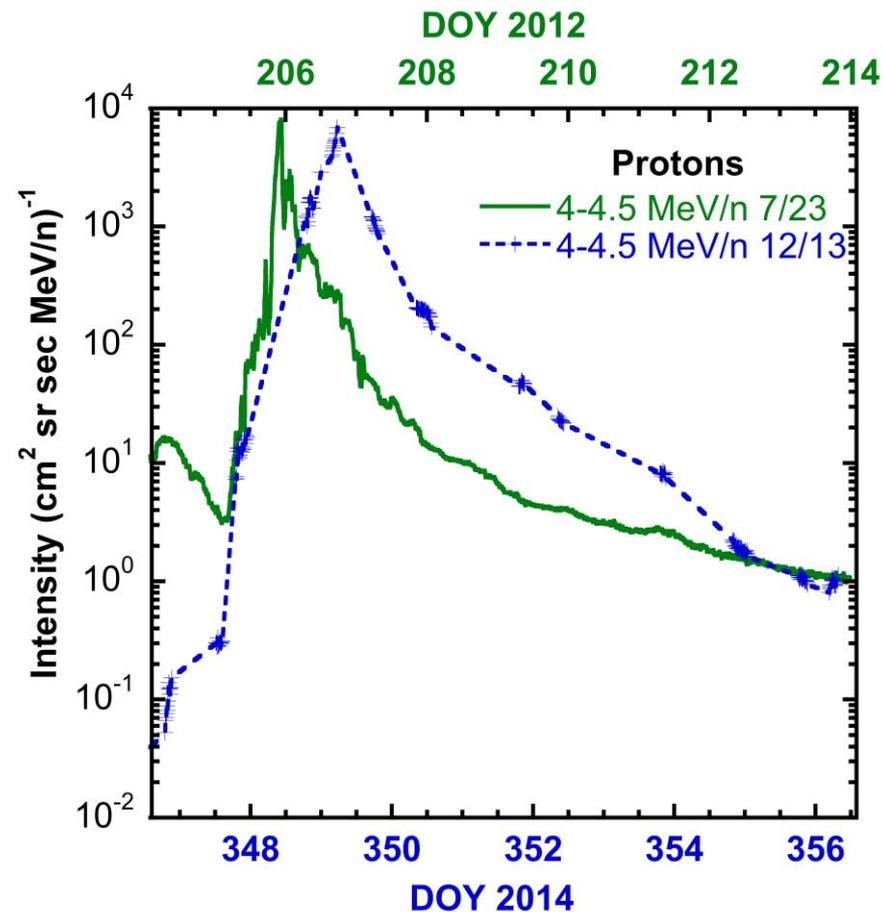
Weak \neq Boring

- 13 December 2014
- STEREO-A sees another



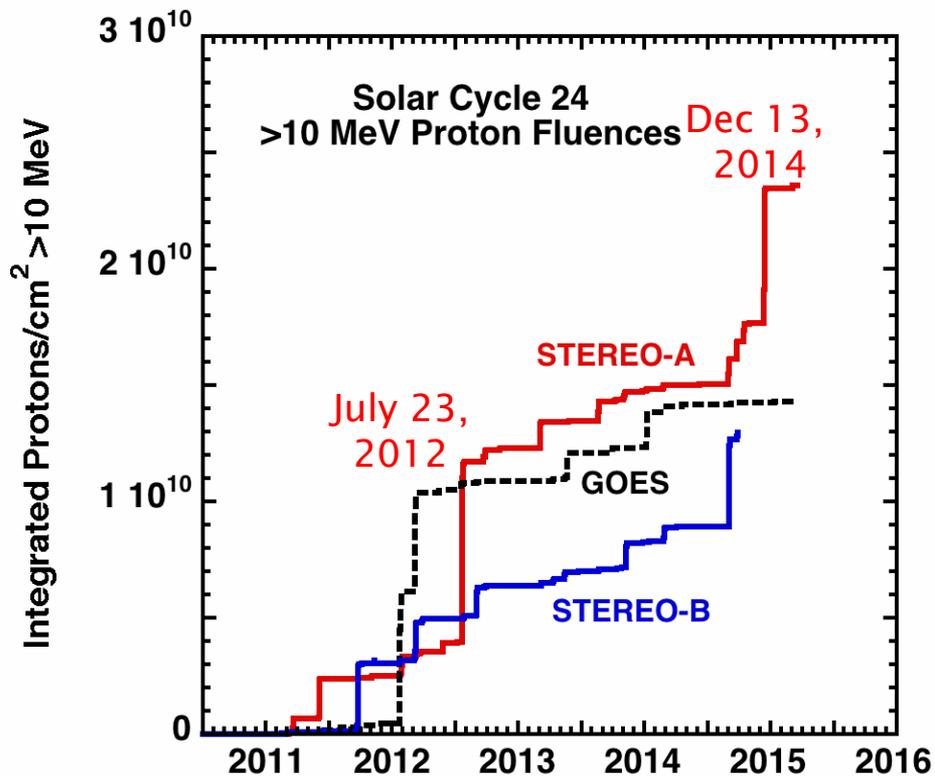
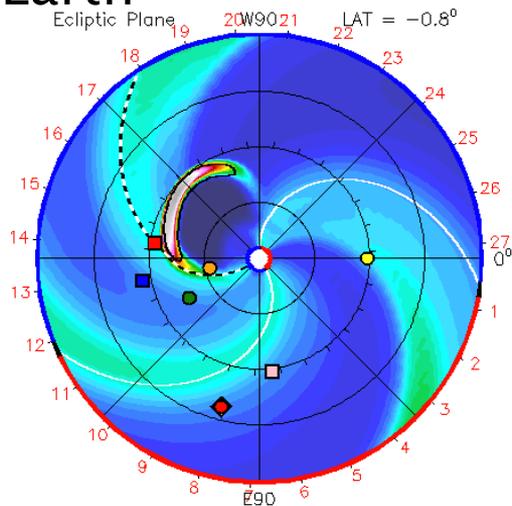
Weak \neq Boring

- 15 December 2014
- STEREO-A sees another
- Gappy data (currently) but comparable to 23 July



Weak \neq Boring

- 13 December 2014
- STEREO-A sees another
- Gappy data (currently) but comparable to 23 July
- Again misses Earth



Lessons Learned

- New Capabilities/Observations
- Answers or **Puzzles**

Lessons Learned

- New Capabilities/Observations
 - 3D CMEs
 - Full Sun source ID
 - Longitudinal studies of SEPs
- Answers or **Puzzles**
 - Where and how fast
 - Backside is important
 - Fast (360°) transport – **how?**

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Lessons Learned

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- Future – Close to the Sun
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Lessons Learned

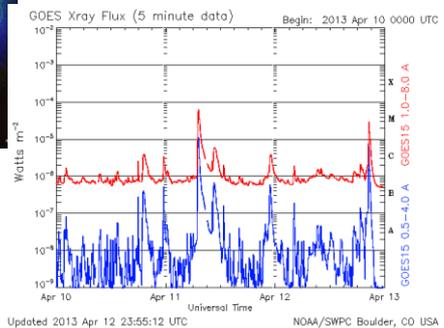
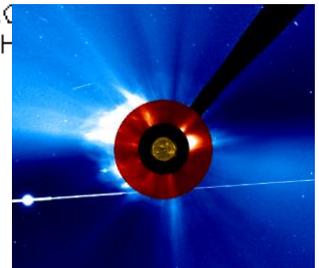
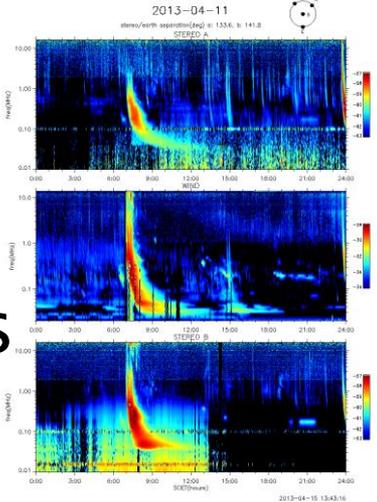
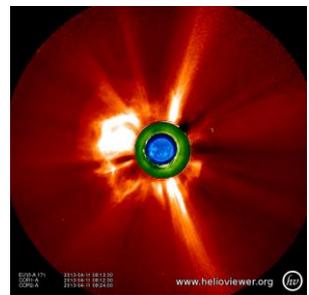
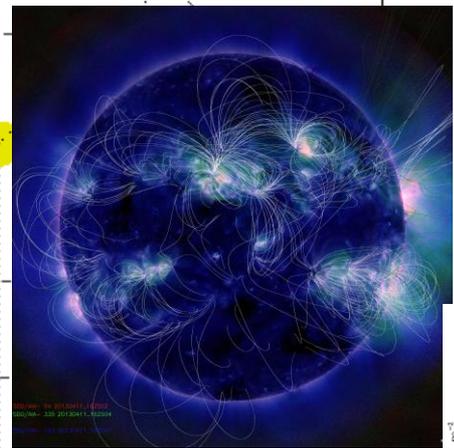
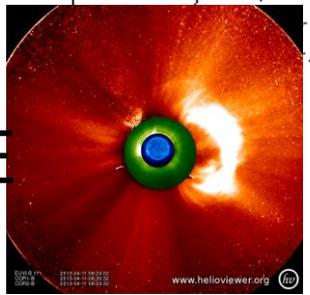
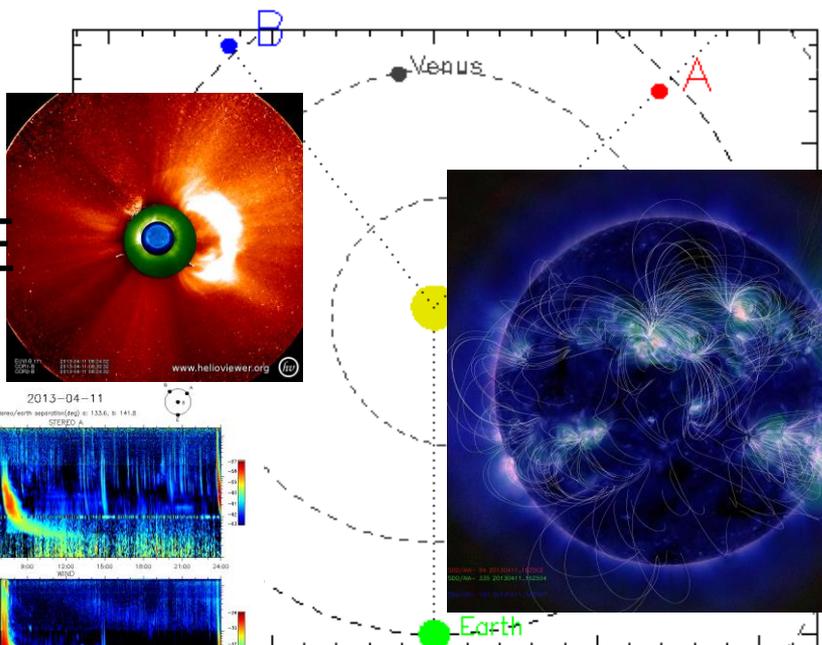
- New Capabilities/Observations
 - 3D CMEs
 - Full Sun source ID
 - Longitudinal studies of SEPs
- New Cycle
 - Weak SEP production
 - Still large events
- Future – Close to the Sun
 - Solar Probe Plus / Solar Orbiter
- Answers or **Puzzles**
 - Where and how fast
 - Backside is important
 - Fast (360°) transport – **how?**
 - **Why? High energy, heavy ions?**
 - Can't be complacent
- New answers and **puzzles**
 - **Turbulence, shocks, SEP seed population, SEPs, much more**



Thank you

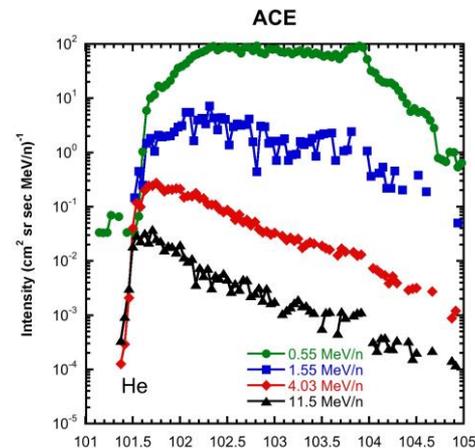
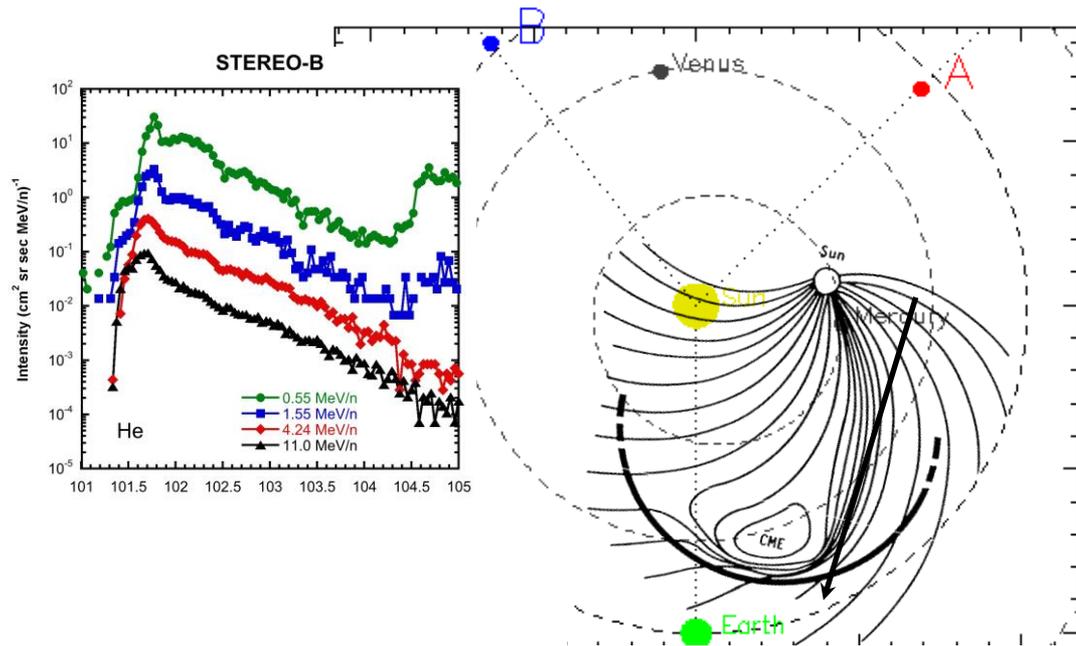
Testing Fe-rich Scenarios

- 11 Apr 2013
- Observed by STB & ACE
- M6.5
- AR11719
- CME
- 900 km/s
- 160°



Updated 2013 Apr 12 23:55:12 UTC NOAA/SWPC Boulder, CO USA

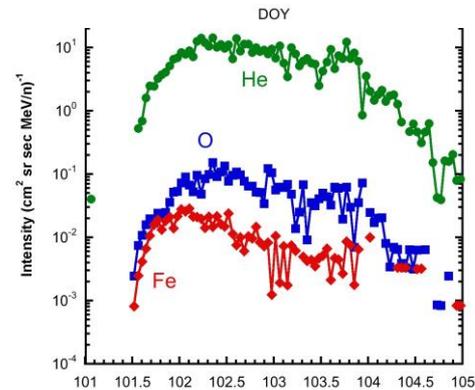
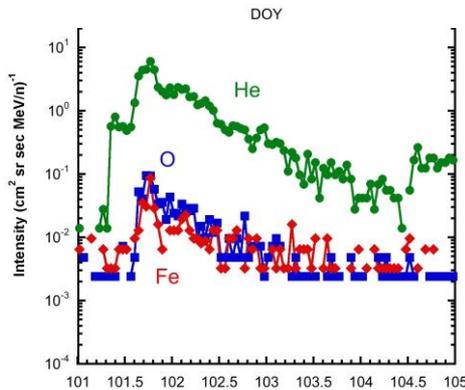
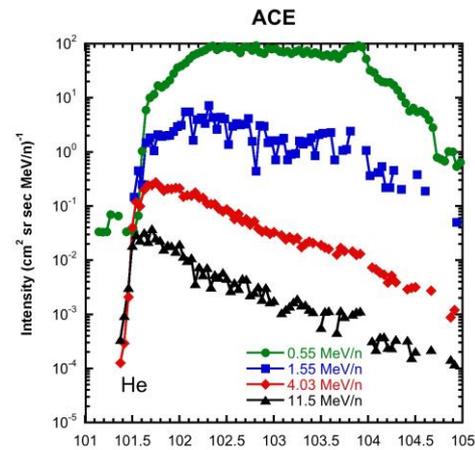
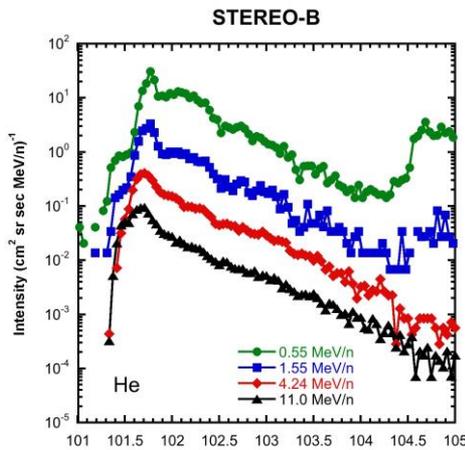
Testing Fe-rich Scenarios



- 142° separation between ACE & STP

Testing Fe-rich Scenarios

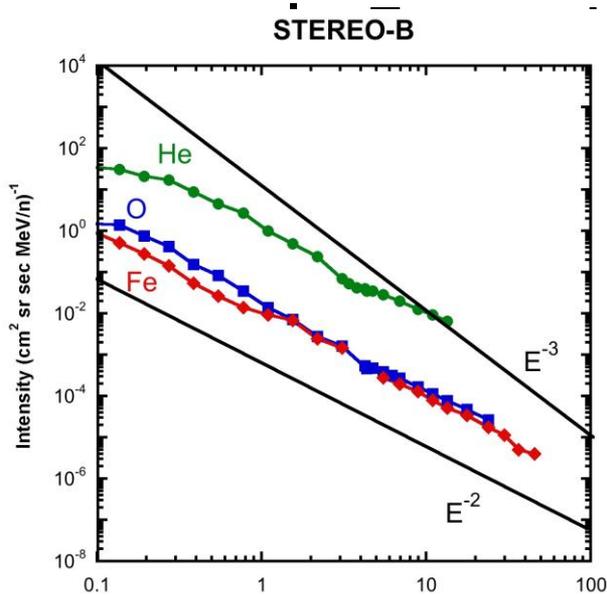
- Observed by ACE and STB in heavies
 - region was over the west limb for STB
 - fast rise at both spacecraft
- Different O and Fe profiles/composition



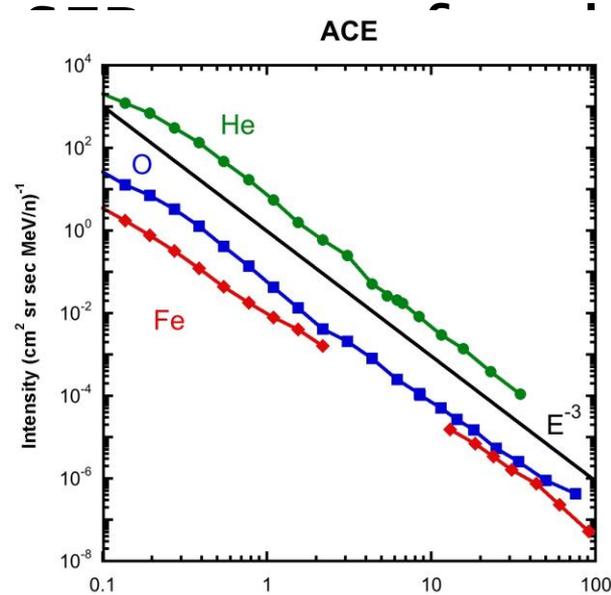
Testing Fe-rich Scenarios

- Event integrated spectra show differences
 - STB has harder spectra, $\sim E^{-2}$ and more Fe-rich
 - ACE has spectra closer to E^{-3} but still Fe-enhanced

• First

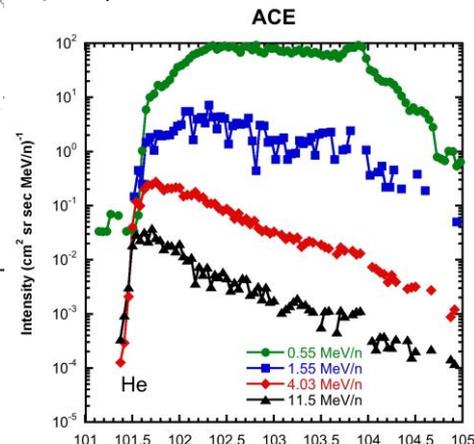
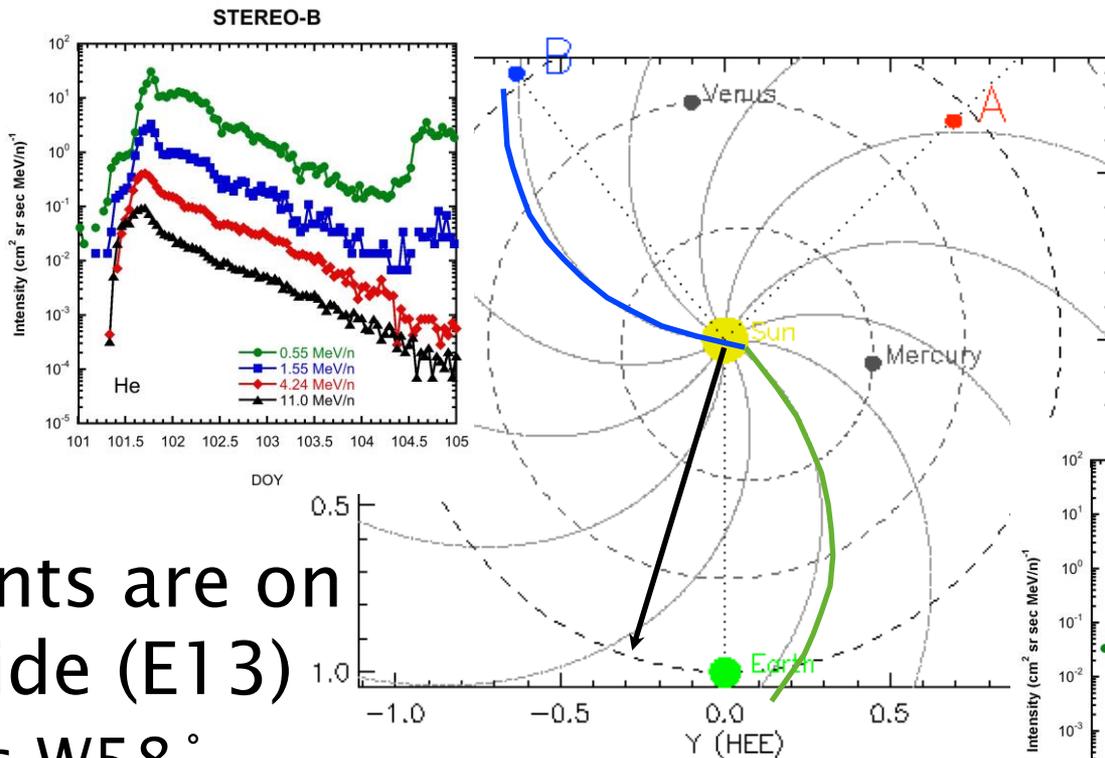


checked



page 24

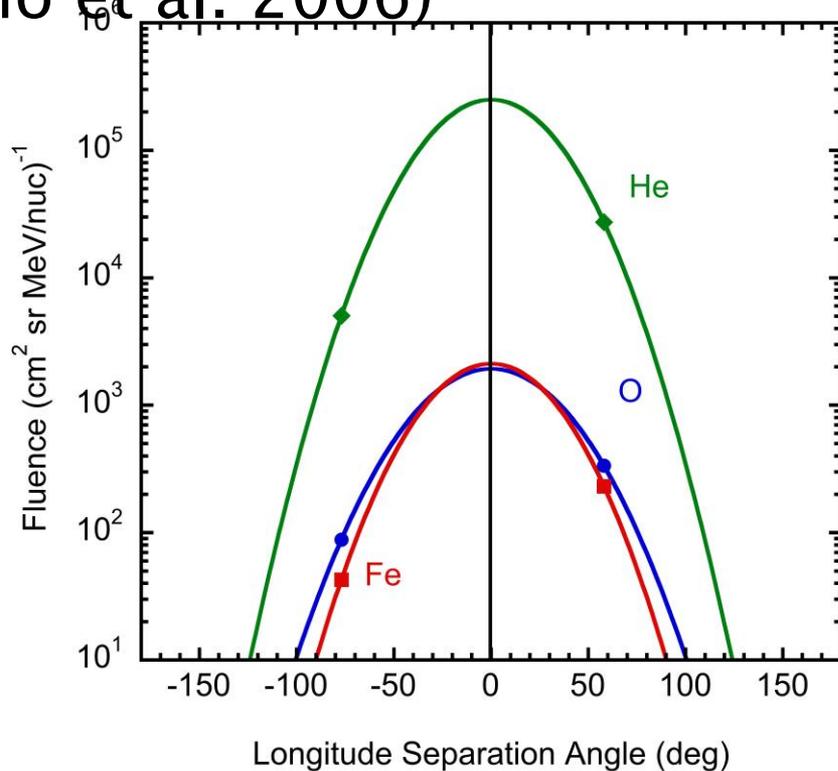
Testing Fe-rich Scenarios



- Footpoints are on either side (E13)
- E77° vs W58°
- Neither is directly

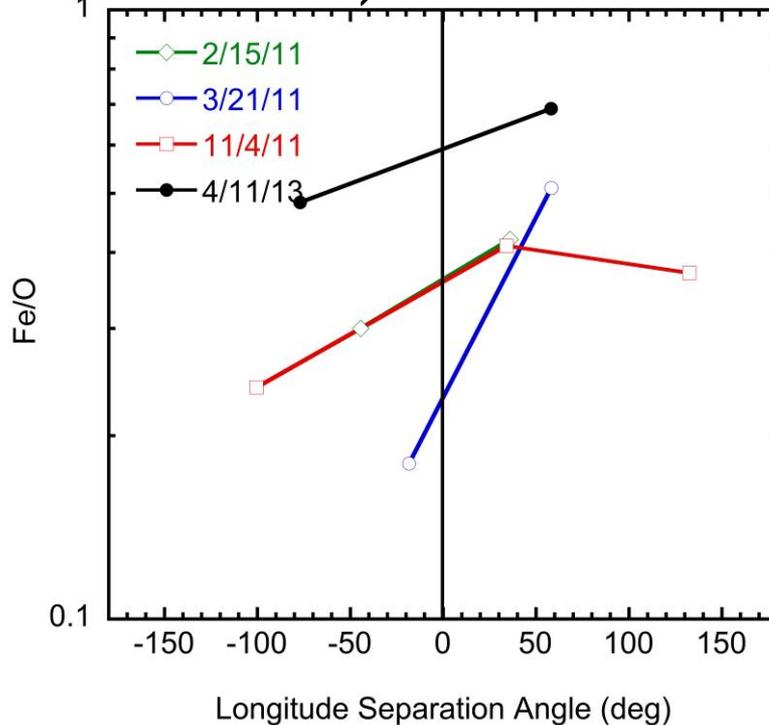
Testing Fe-rich Scenarios

- Longitude dependence
 - Fitting a Gaussian (Lario et al. 2006)
 - $\sigma = 27^\circ, 31^\circ, 28^\circ$
 - Narrower than typical ($\sigma = 45-50^\circ$)
 - Suggests $\text{Fe}/\text{O} \sim 1$ at flare connection



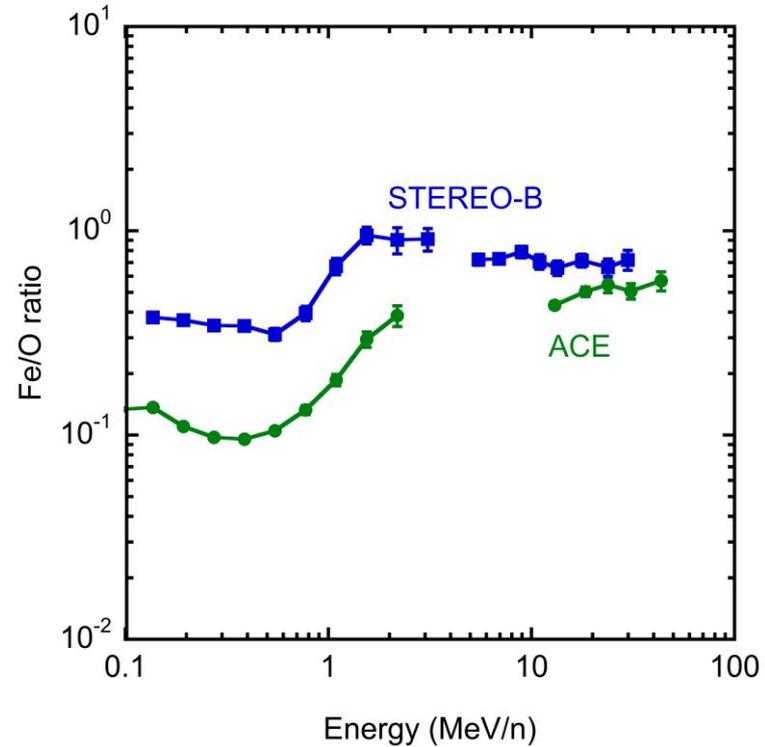
Testing Fe-rich Scenarios

- Longitude dependence
 - Fitting a Gaussian (Lario et al. 2006)
 - $\sigma = 27^\circ, 31^\circ, 28^\circ$
 - Narrower than typical ($\sigma = 45\text{-}50^\circ$)
 - Suggests $\text{Fe}/\text{O} \sim 1$ at flare connection
 - Compared to other \sim Fe-rich events
 - Not a strong consensus on direct flare contrib.



Testing Fe-rich Scenarios

- Fe/O increasing with energy? Yes
 - STB reaches higher Fe/O values but starts higher
 - ACE+STB E dependence is very similar



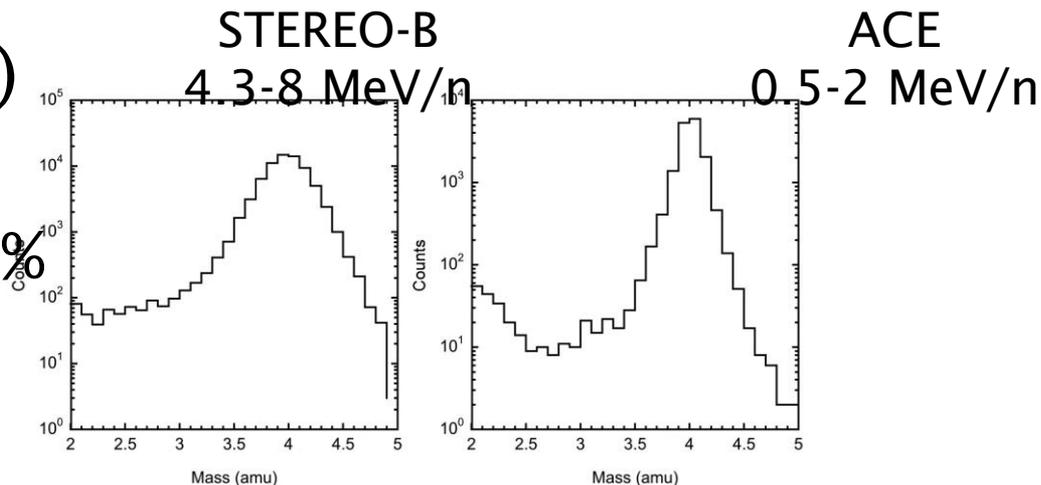
Testing Fe-rich Scenarios

- Fe/O increasing with energy? Yes

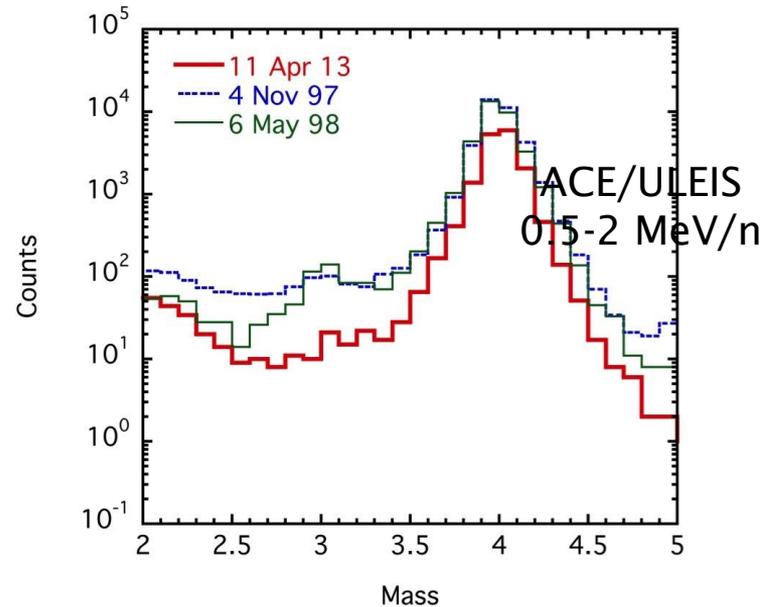
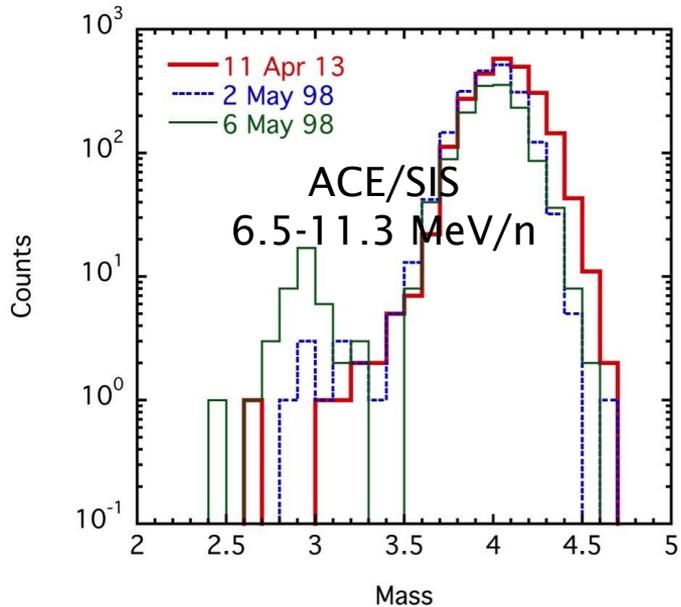
- STB reaches higher Fe/O values but starts higher
- ACE+STB E dependence is very similar

- Enhanced ^3He ? No (!)

- LET: $^3\text{He}/^4\text{He} < 4\%$
- ULEIS: $^3\text{He}/^4\text{He} < 0.07\%$
- SIS: $^3\text{He}/^4\text{He} < 1\%$



Testing Fe-rich Scenarios



- ULEIS: $^3\text{He}/^4\text{He} < 0.07\%$

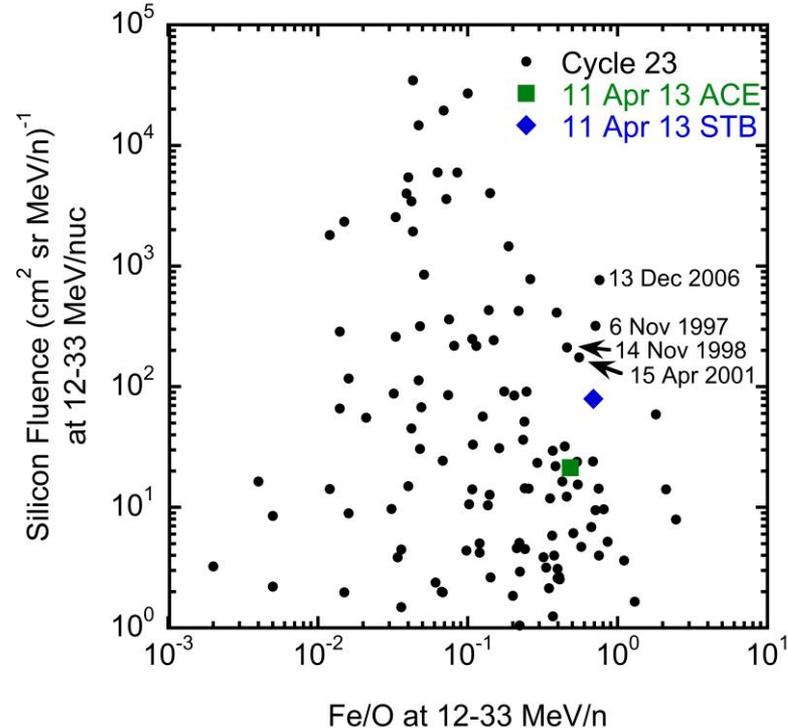
- SIS: $^3\text{He}/^4\text{He} < 1\%$

- Much less ^3He compared to cycle 23 events

6 May 98: 10% $^3\text{He}/^4\text{He}$ vs 10-50-10%

Testing Fe-rich Scenarios

- Fe-rich compared to cycle 23 events?
 - Similar to 13 Dec 2006 and 6 Nov 1997



Testing Fe-rich Scenarios

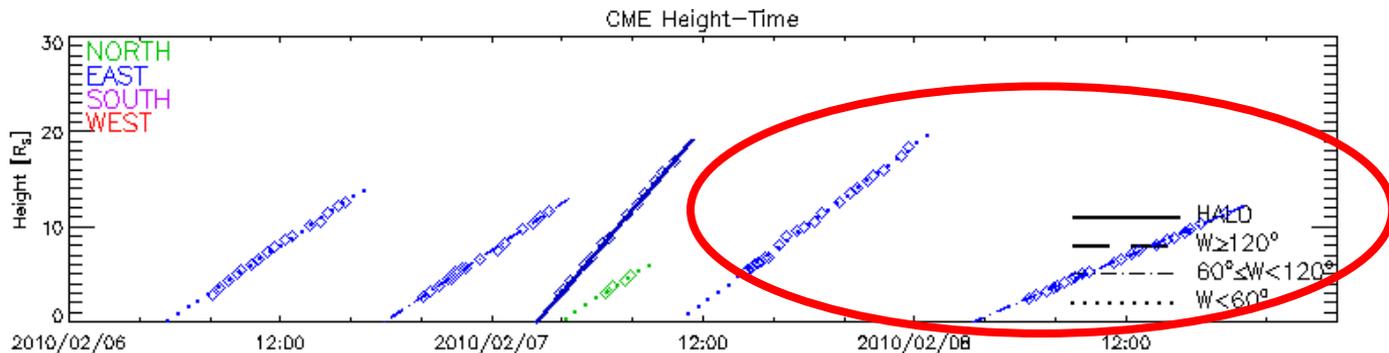
- Fe-rich compared to cycle 23 events?
 - Similar to 13 Dec 2006 and 6 Nov 1997
 - But less ^3He (although 13 Dec 2006 had little ^3He)
- Direct flare contribution scenario
 - Most closely connected spacecraft has higher Fe/O
 - No ^3He - problem
- Suprathermals + Shock Orientation
 - Requires different shock orientation or suprathermals at ACE & STB
 - No ^3He - problem

What We Don't Understand

- ^3He is not always confined to a narrow range
 - Potential issue for Fe-rich scenarios
 - *Q: What governs when ^3He spreads widely?*
 - *Q: How is ^3He spread widely?*
- Many events are from backside
 - Space weather prediction issue
 - *Q: How are SEPs transported so quickly to far longitudes?*
 - *Q: Is this a 'near-Sun' or interplanetary effect?*
- Tests of Fe-rich scenario inconclusive
 - *Q: Does ^3He need to go with Fe-rich?*

Results

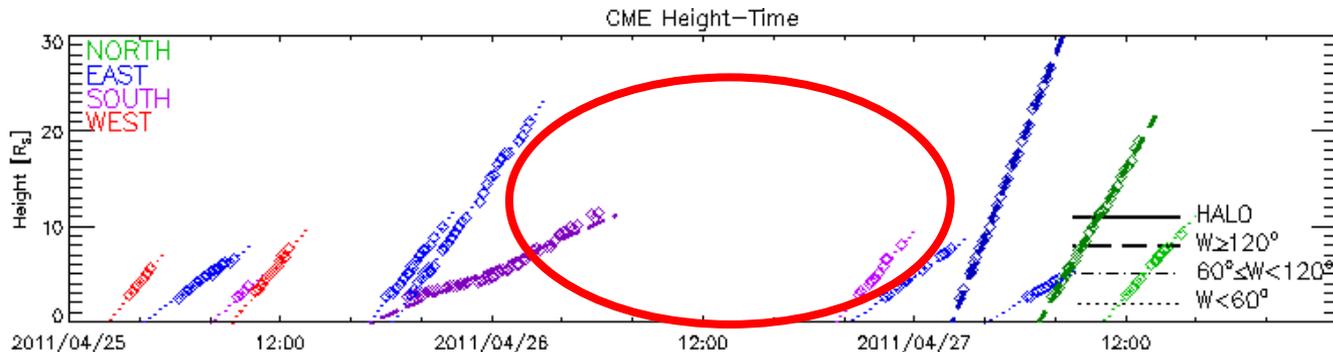
- 7 Events
- Typically get $\sigma \sim 15\text{-}35^\circ$
 - Narrower than multi-spacecraft events
- Differences?
 - Presence of preceding CMEs



7 Feb 2010

Results

- 7 Events
- Typically get $\sigma \sim 15\text{-}35^\circ$
 - Narrower than multi-spacecraft events
- Differences?
 - Presence of preceding CMEs
 - Some single-s/c events have preceding CMEs



26 Apr 2011

Results

- 7 Events
- Typically get $\sigma \sim 15\text{-}35^\circ$
 - Narrower than multi-spacecraft events
- Differences?
 - Presence of preceding CMEs
 - Some single-s/c events have preceding CMEs
 - But only 2 were wider than 90°
 - And those had $v < 300$ km/s
 - vs 7 Feb 2010 had a halo at 421 km/s