PAMELA Measurements of Magnetospheric Effects on High Energy Solar Particles

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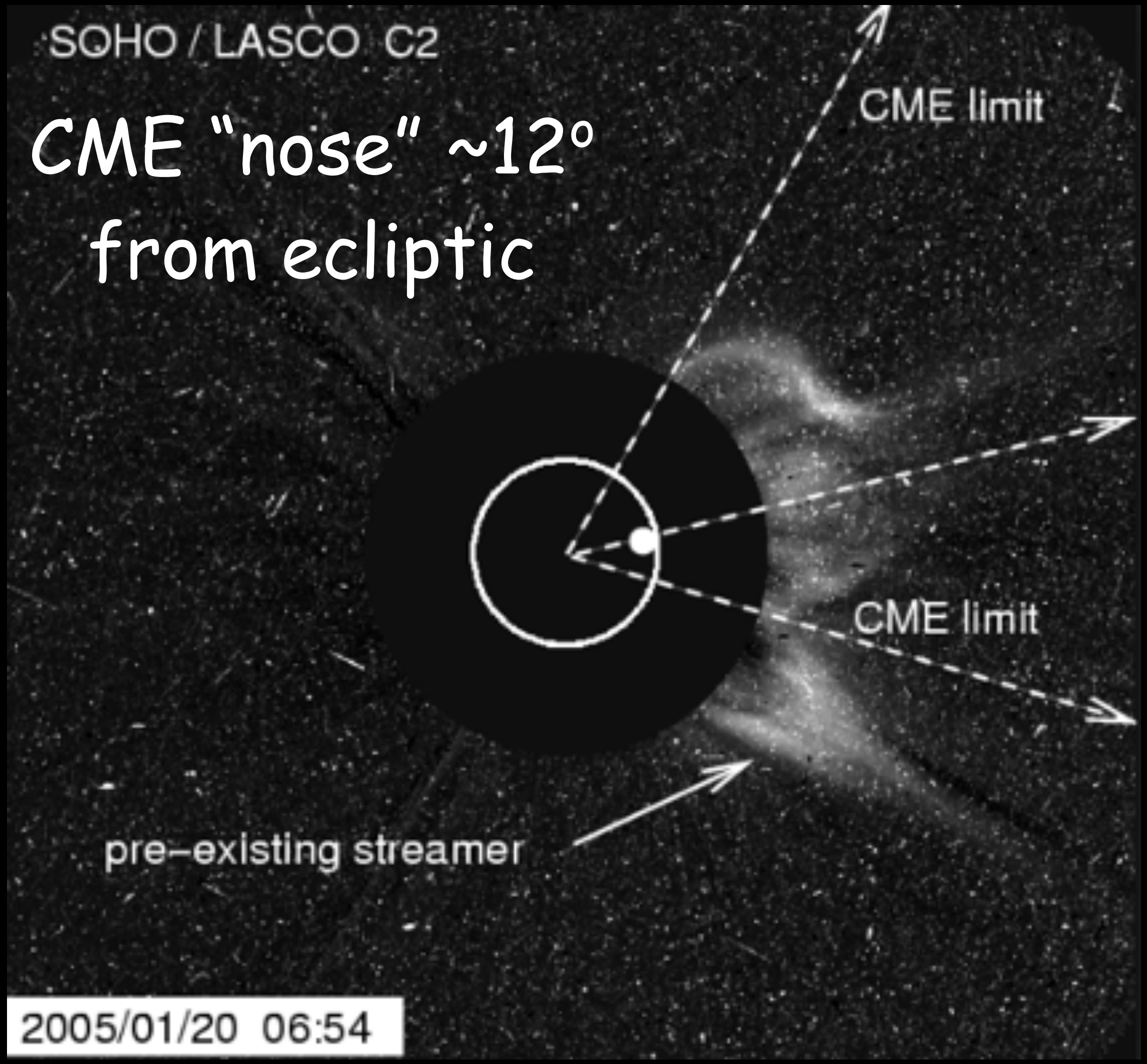
NASA/GSFC

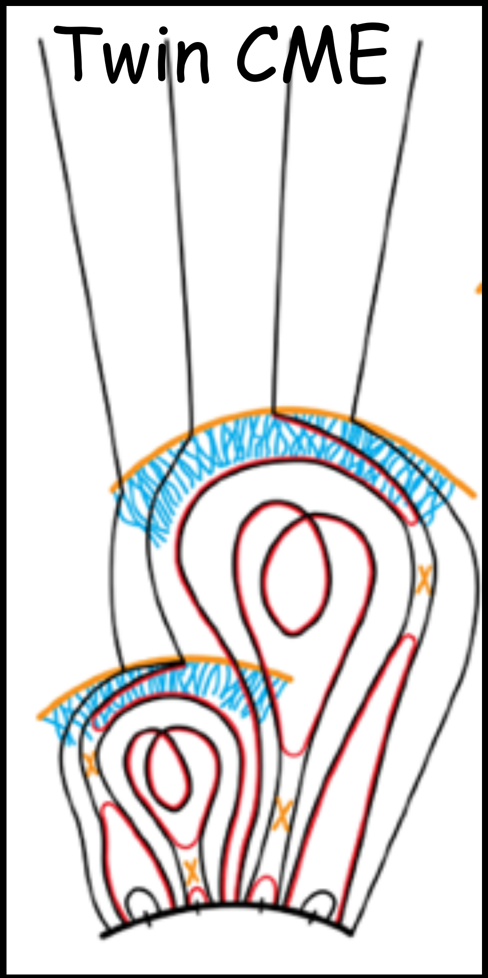
On behalf of the PAMELA Collaboration

Origin of GLEs

- **Flare : Reconnection**
  - Prompt, anisotropic signal whereas shock needs time
- **Shocks formed from Coronal Mass Ejection (CME)**
  - Delay in II radio emission
  - Twin CMEs?
  - CME orientation?
- **Transport?**
  - Unusual morphology

Solar Flare





Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA).

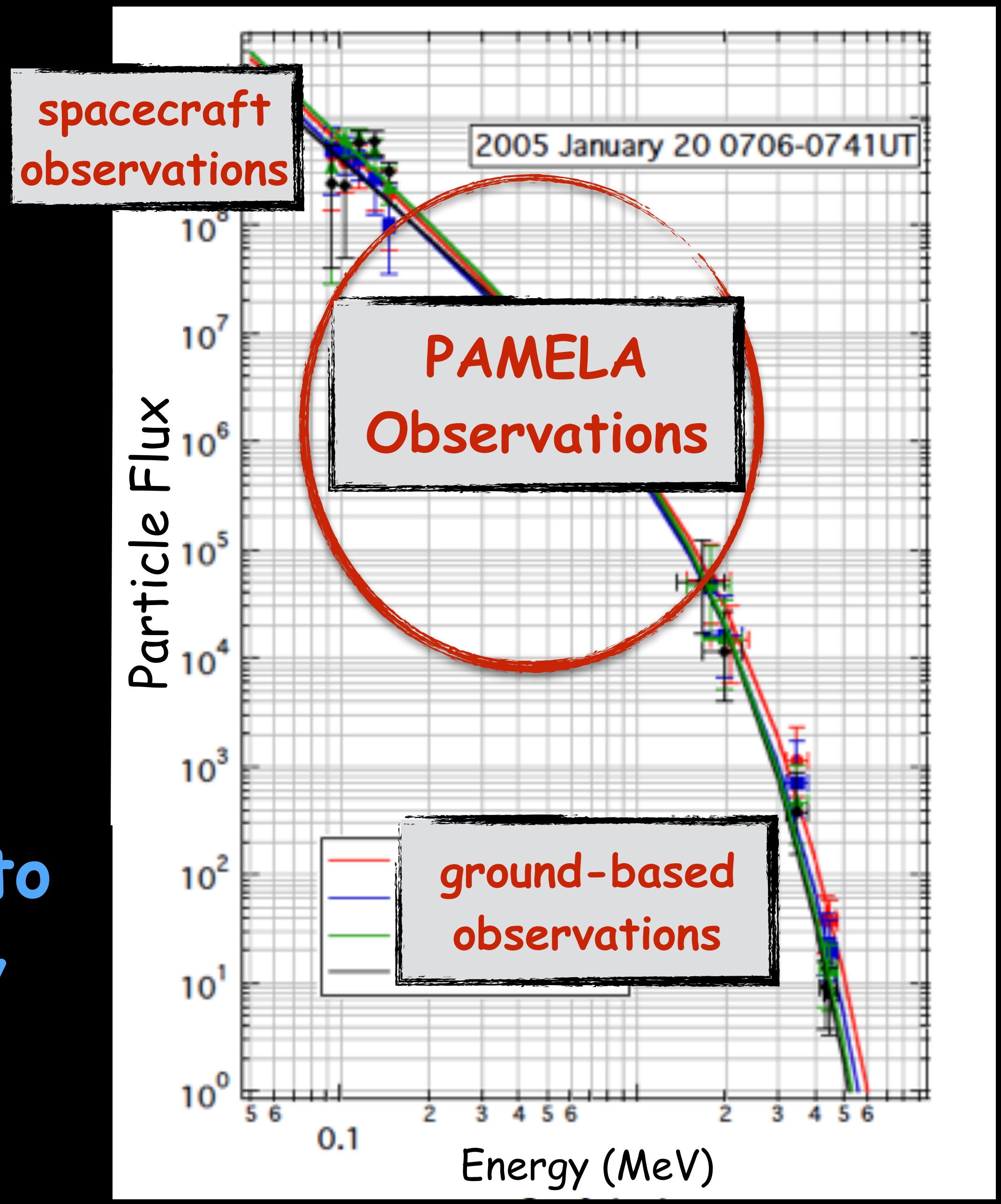
LARGE energy range (80 MeV to tens of GeV)

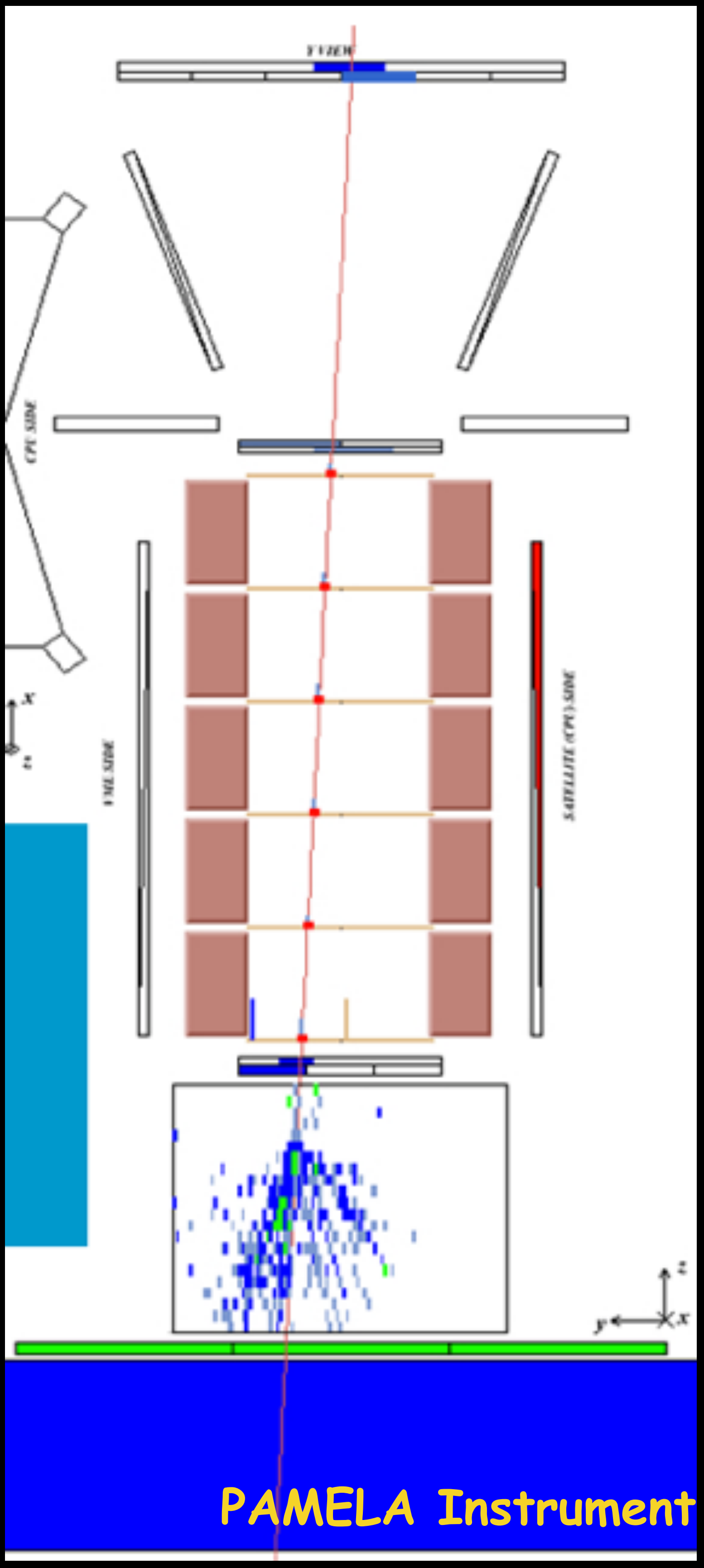
Particle direction

Composition

Three capabilities to provide a completely new view of GLEs!

Morgan & Ryan 2015





High-energy SEPs from PAMELA

PAMELA Start (Day/UT)	GOES Max (Day/UT)	Proton pfu>10 MeV	CME Speed (km/s)	Flare Time (Day/UT)	Class	Location	GLE	Fermi/LAT
2011 Mar 21/1950	Mar 22/0135	14	NW 21 0236	Farside				
2011 Jun 07/0820	Jun 07/1820	72	Halo 07 0803	Jun 07 0641	M2/2N	S21W64		0747UT σ~10.35
2011 Sep 06/0135	—		2240		M5.3	14/07		2212UT σ~23.32
2011 Sep 06/2212	—		2305		X2.1	14/18		
2011 Nov 04/0260	—		125		C5.4	19/-61		
2012 Jan 23/0530	Jan 24/1530	6310	Halo 23 0400	Jan 23/0359	M8 Long dur.	N28W36	Unseen GLE	0545UT σ~6.98
2012 Jan 27/1905	Jan 28/0205	796	Halo 27 1827	Jan 27/1837	X1 Long dur.	N27W71	Unseen GLE	1939UT σ~3.94
2012 Mar 07/0510	Mar 08/1115	6530	Halo 07 0036	Mar 07 0024	X5/3B	N17E15	Unseen GLE	0823UT σ>60
2012 Mar 13/1810	Mar 13/2045	469	Halo 13 1736	Mar 13 1741	M7	N18W62	Unseen GLE	
2012 May 17/0210	May 17/0430	255	Partial Halo 17/0148	May 17 0147	M5	N12W89	GLE 71	0213UT σ~3.16
2012 Jul 07/0400	Jul 07/0745	25	Halo (asym) 06/2312	Jul 06/2308	X1	S18W50		2326UT σ~11.02
2012 Jul 08/1623	—		1736		M6.9	-17/74		
2012 Jul 19/0417	—		524		M7.7	-28/65		
2013 Apr 11/1055	Apr 11/1645	114	Asym Full Halo 11/0724	11/0716	M6	N09E12	Unseen GLE	0702UT σ~8.58
2013 Apr 24/0117	—		48		C1.4	14/46		
2013 May 22/1420	May 23/0650	1660	Asym Halo 22/1325	22/1332	M5 Long dur.	N15W70		
2013 Oct 28/0601			1536		M1.5			1545UT
2013 Nov 11/0446	—		448		C8.2	-23/4		
2014 Jan 06/0915	Jan 06/—	42	1960	—	—	farside	GLE 72	
2014 Feb 25/1355	Feb 28/0845	103	Asym. Halo 25/0130	25/0049	X4	S12E82		0110UT σ~55.63
2014 Apr 18/1525	Apr 19/0105	58	CME (C3) 18/1325	18/1303	M7	S16W41		
2015 Jun 21(?)	Jun 21/ 2135	1070	Full Halo 21/0236	21/0236	M2	N13W00		0519UT σ~3.2

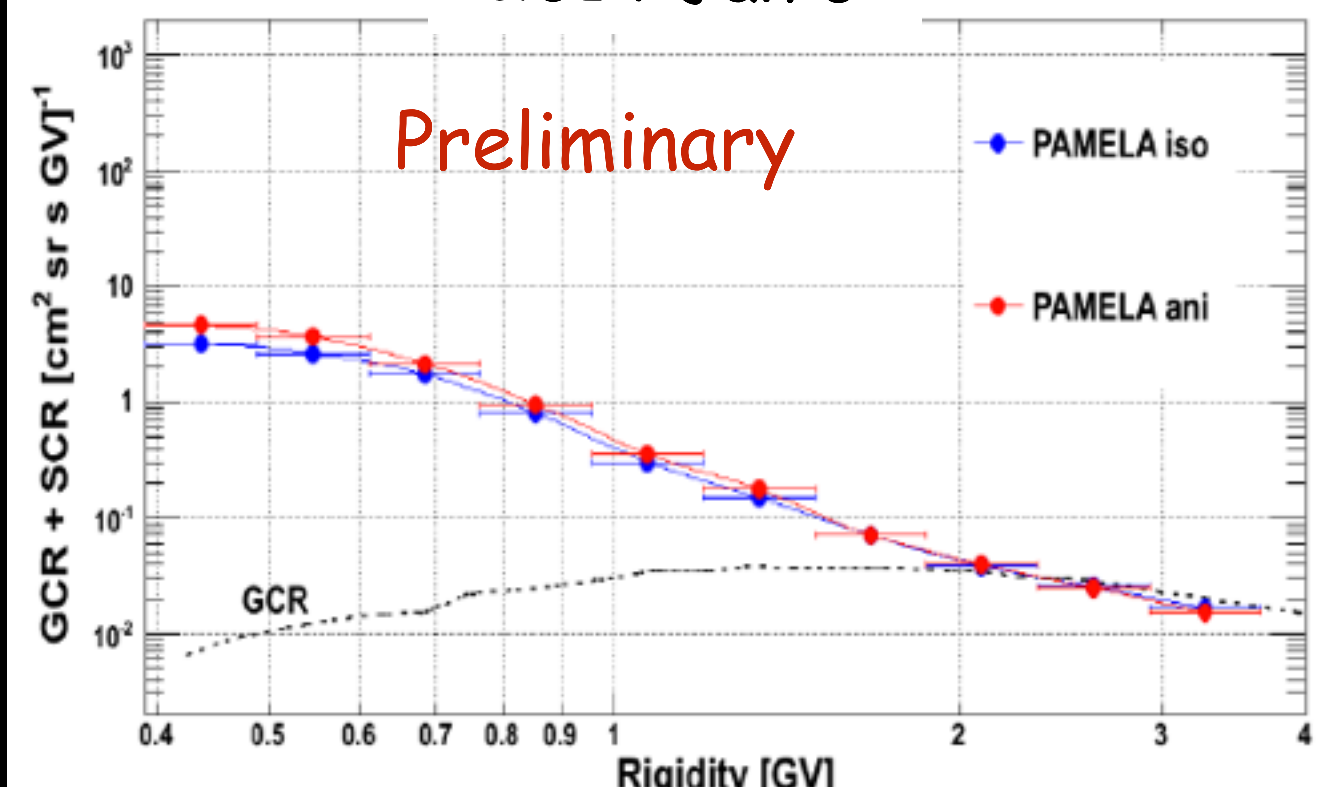
- >20 SEPs observed
- Several observed event onsets (2011 Jun 7; 2014 Jan 14)
- 2 confirmed GLEs (& one in solar cycle 23), and 5 possible GLEs that were missed by neutron monitors — (Christian et al. ICRC 2015)
- 10 of the SEPs (almost 1/2!) are also associated with > 100 MeV emission from Fermi/LAT

GLEs of Cycle 24

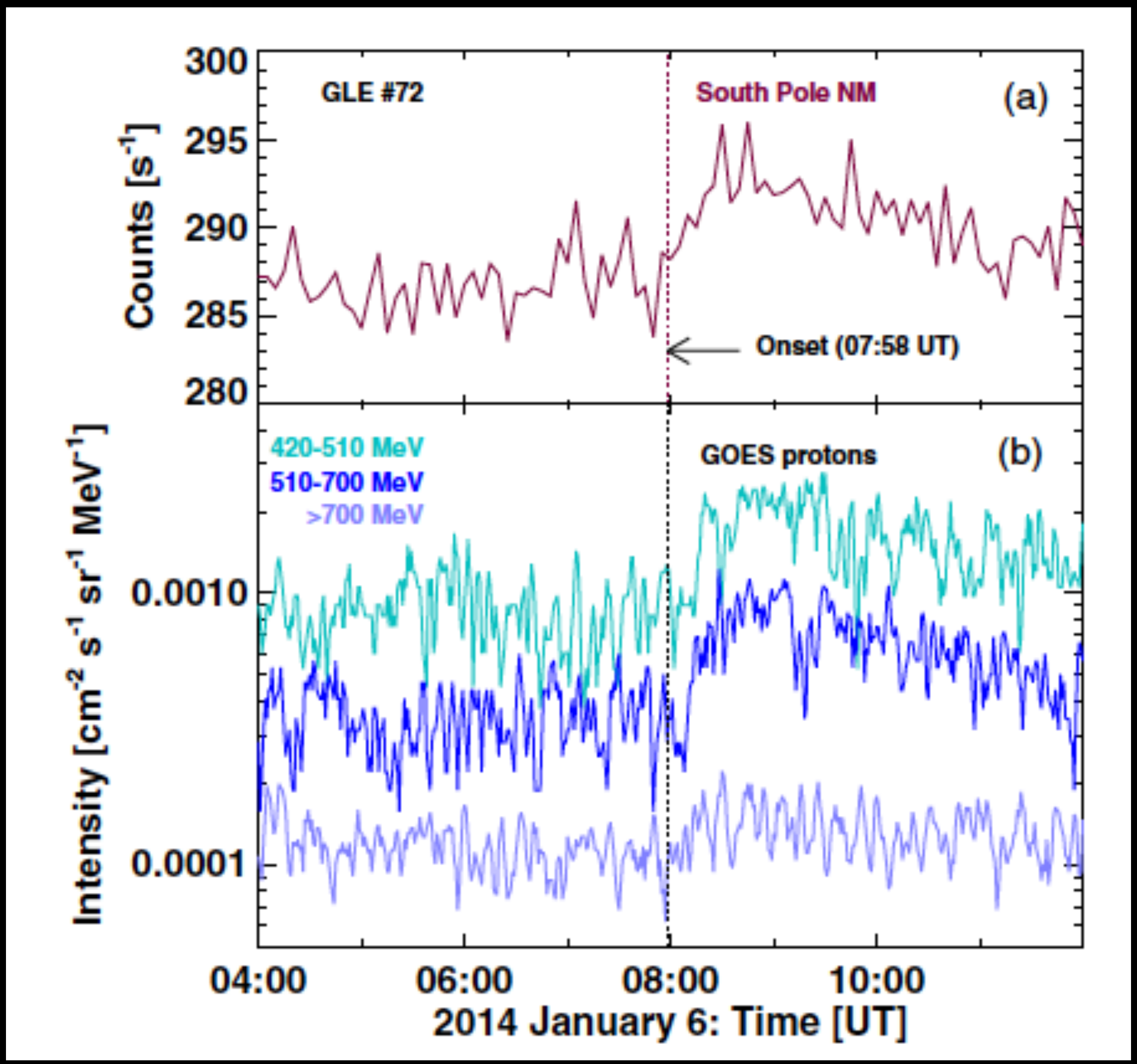
Three confirmed GLEs to date:

- GLE 70   13-Dec-2006
  (Adriani et al. 2011)
- GLE 71   17-May-2012
  (Adriani et al. 2015)
- GLE 72   06-Jan-2014
  backside event

2014 Jan 6



2014 Jan 6 GLE (Thakur et al. 2014)



A. Bruno (next talk)

GLEs of Cycle 24

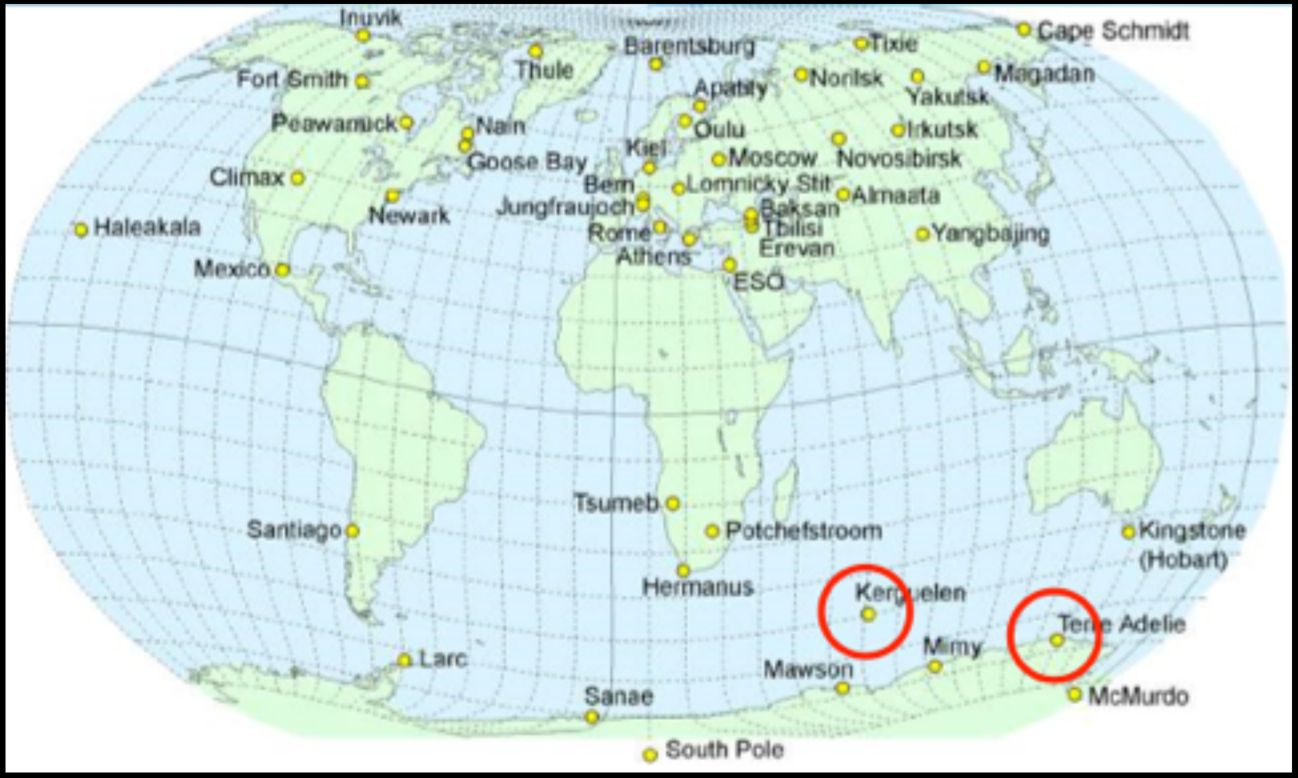
Other potential GLE candidates?
– 2012-Jan-27 (likely missed GLE)

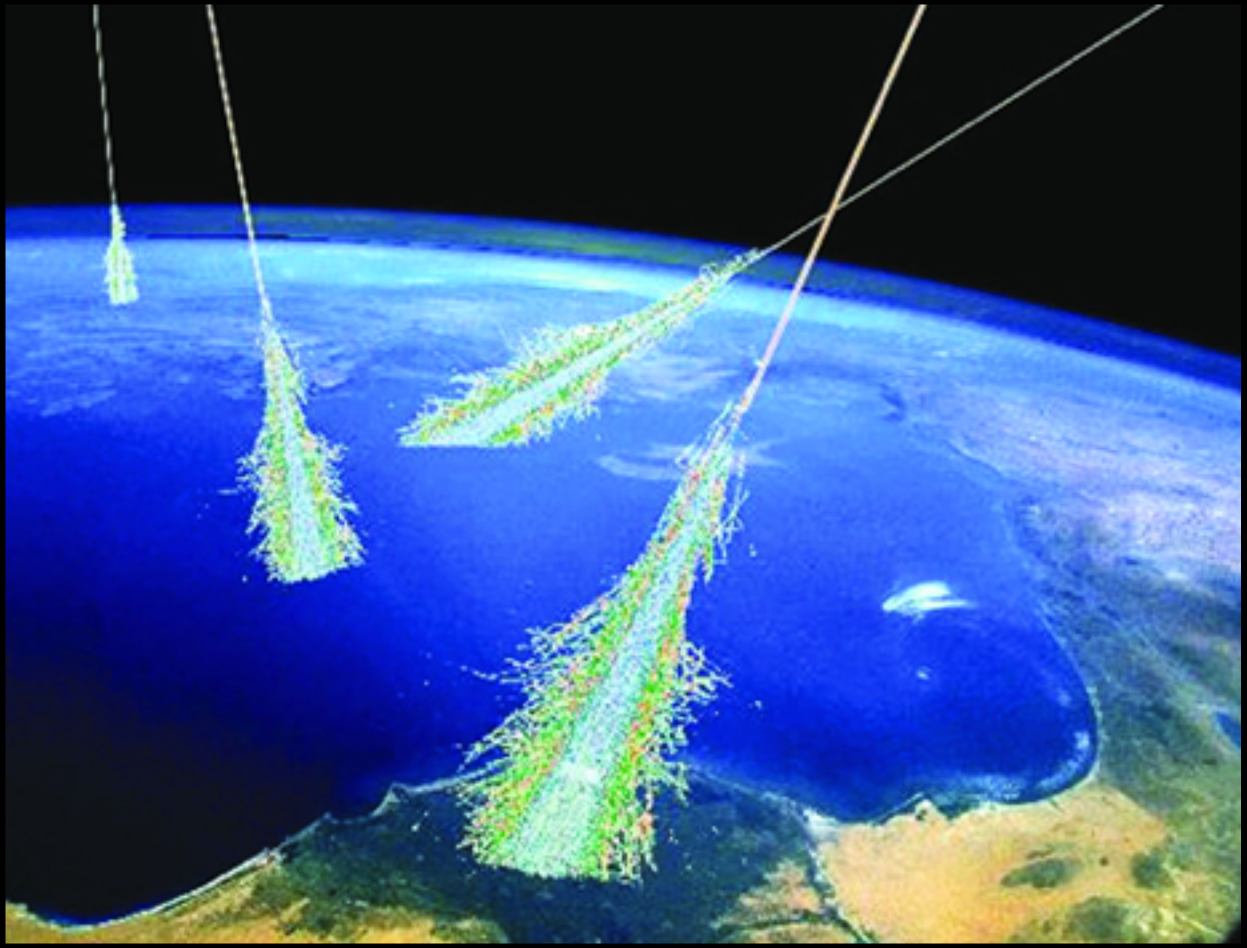
PAMELA 1 GeV Rank	Date	Notes
1	13 Dec 2006	GLE 70
2	17 May 2012	GLE 71
3	27 Jan 2012	Reported by Belov et al. Probable Unseen GLE
4	06 Jan 2014	GLE 72
5	07 Jun 2011	No neutron monitor signal
6	25 Feb 2014	No neutron monitor signal
7	22 May 2013	No neutron monitor signal
8	06 Sep 2011	No neutron monitor signal
9	07 Mar 2012	Reported by Belov et al. Possible Unseen GLE. PAMELA not in good position early in flare.
10	08 Jul 2012	No neutron monitor signal
11	28 Oct 2013	No neutron monitor signal
12	13 Mar 2012	Reported by Belov et al., but nm signal has inconsistent time profile.
16	11 Apr 2013	Reported by Nicoll and Harrison. No other indication of HE particles especially near UK.
24	23 Jan 2012	Reported by Makhmutov et al. PAMELA does not see high energy particles and no nm signal. Beam missed?

2012 May 17th GLE

- PAMELA sees first GLE of solar cycle 24, May 17th 2012
- Unlike 2006 Dec. 13th GLE, PAMELA was able to detect the anisotropic phase of the event.
- Unique opportunity for PAMELA to examine the origin of the highest energy solar energetic particles.

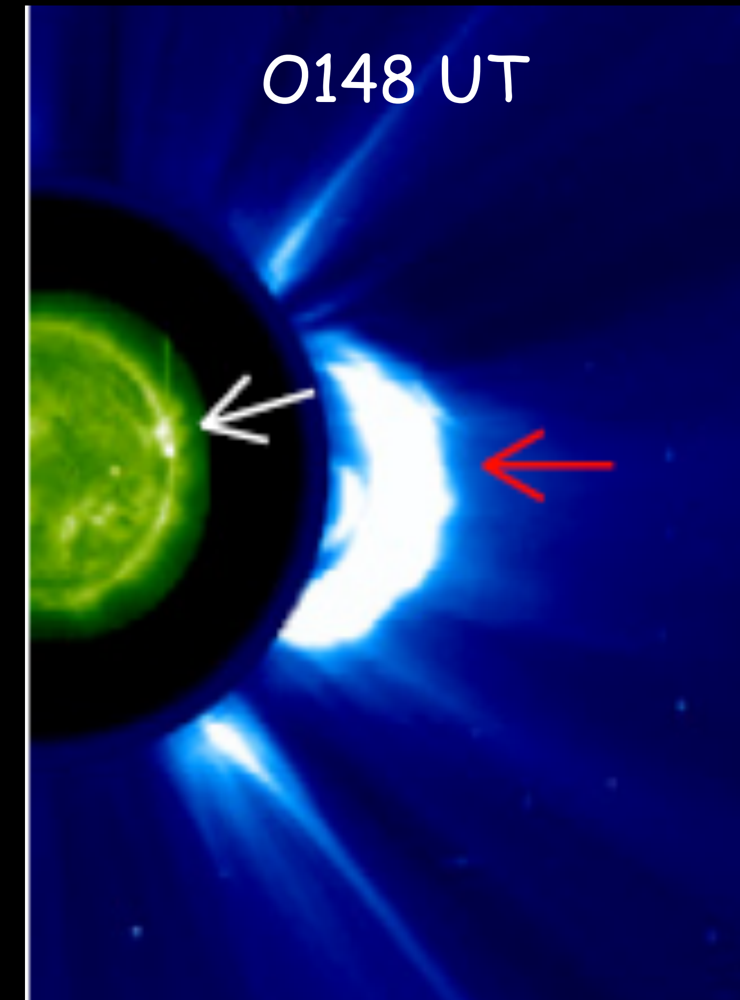
Neutron Monitor Network

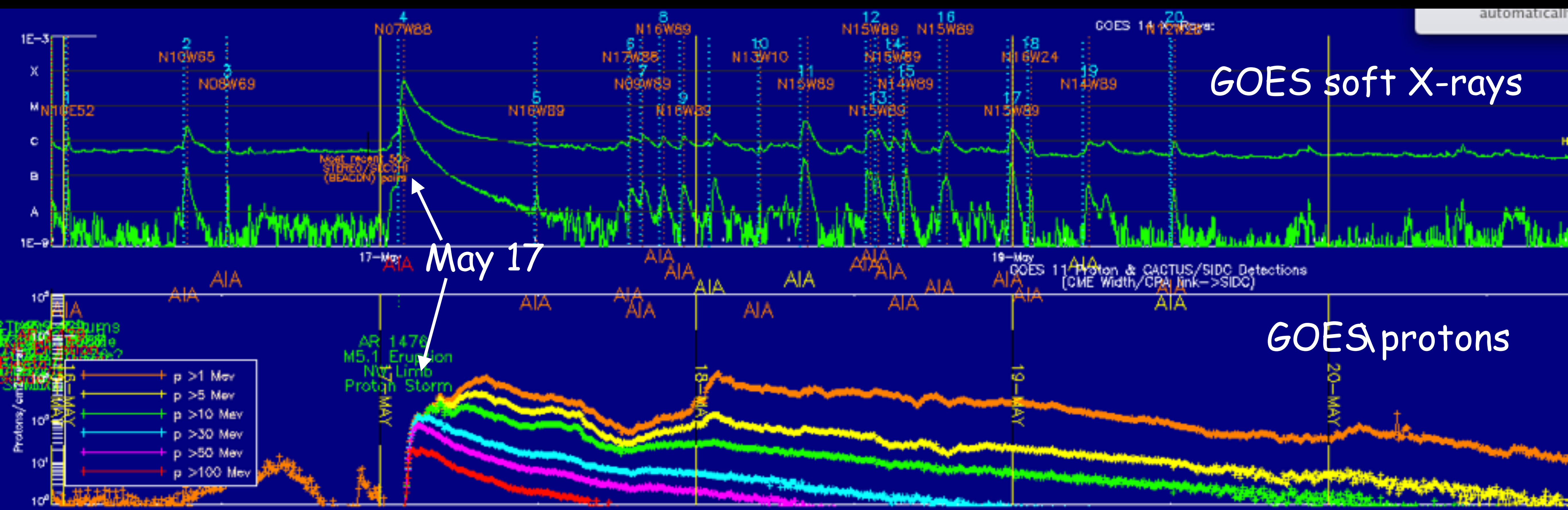




Contextual Data for 2012 May 17th

- Associated with M5.1 flare (rare!) in AR11476 located at N07W88 -well connected.
- GOES Soft X-ray onset at 0125 UT (duration of 22 min); Type II radio burst at 0131 UT; extended > 100 MeV gamma-ray emission observed from Fermi/LAT. CME present with speed 1582 km/s (max speed 1997 km/s)

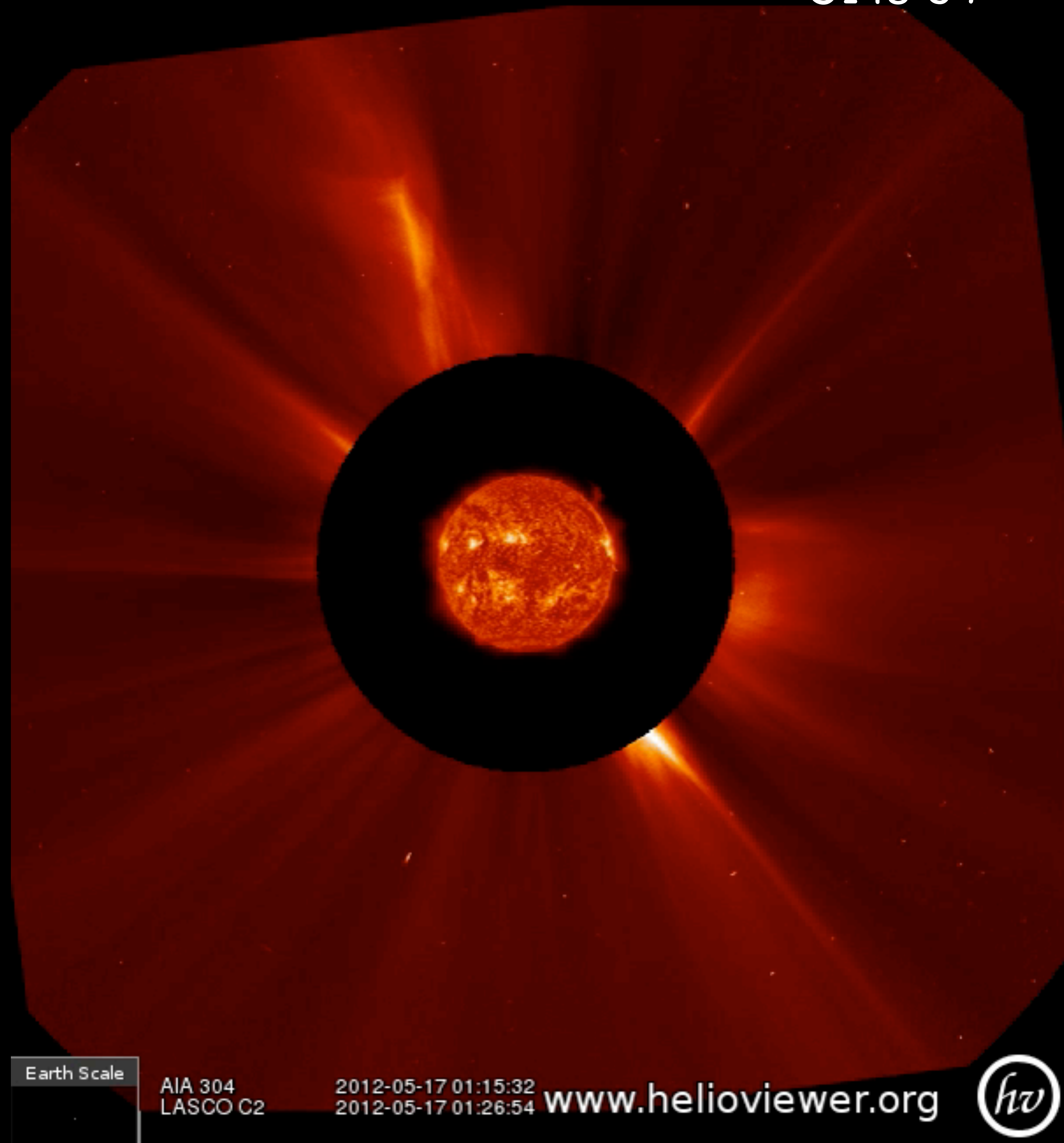




High-Energy Event of 2012 May 17th

0148 UT

- PAMELA sees first Ground Level Enhancement of solar cycle 24, May 17th 2012
- Associated with a surprisingly small flare but fast CME
- 2012 NASA Nugget "Catching Solar Particles Infiltrating Earth's Atmosphere"



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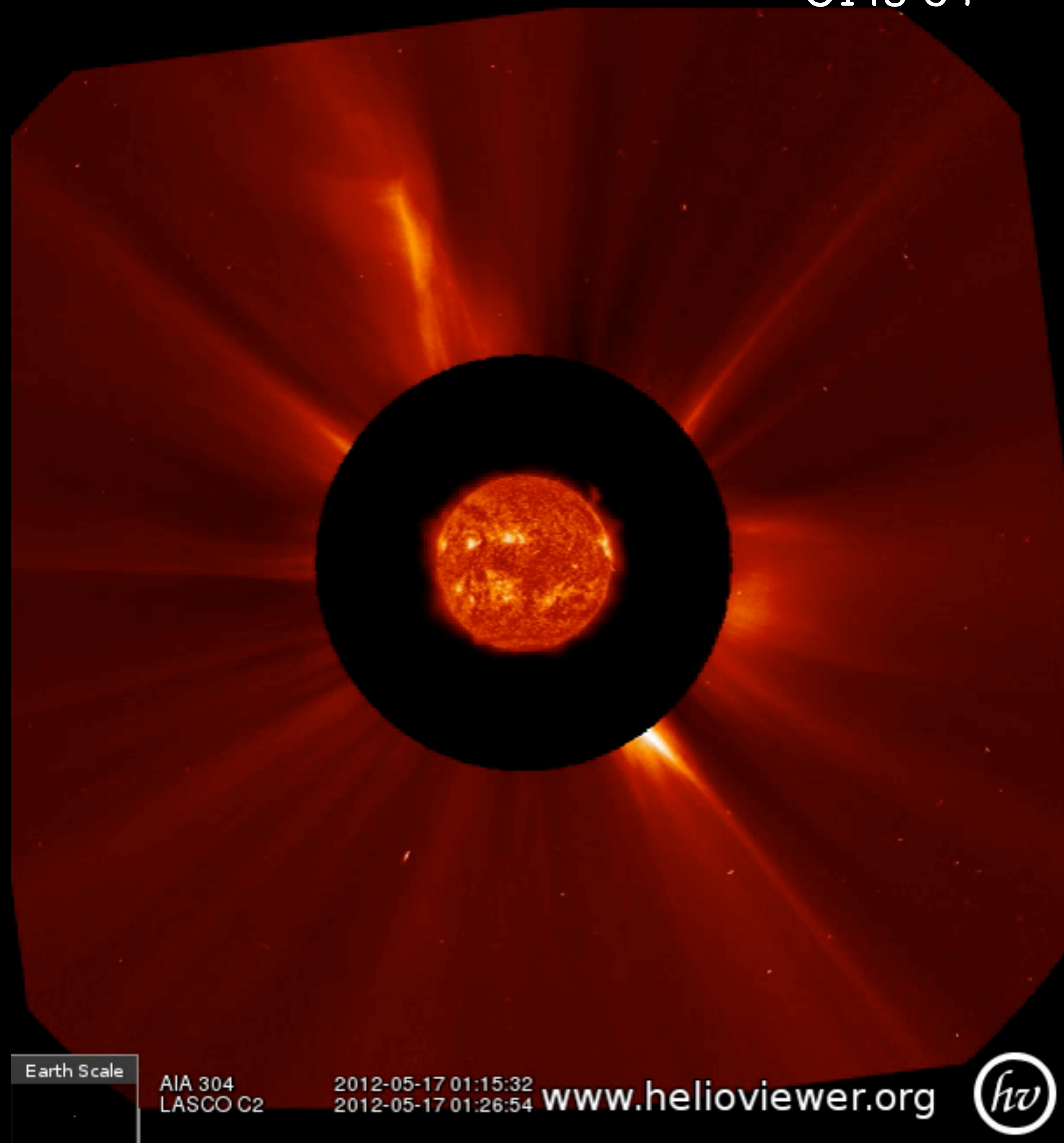
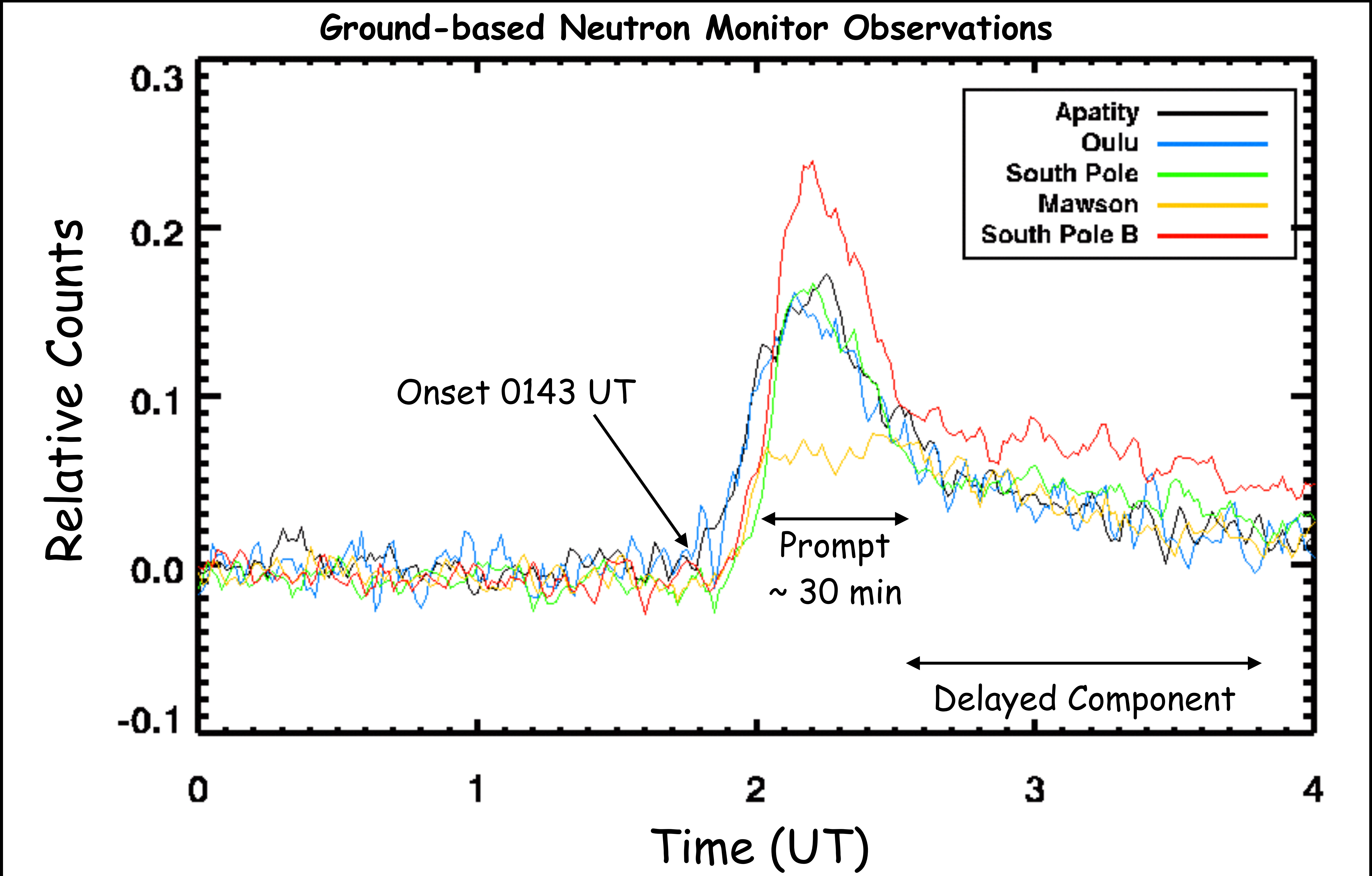


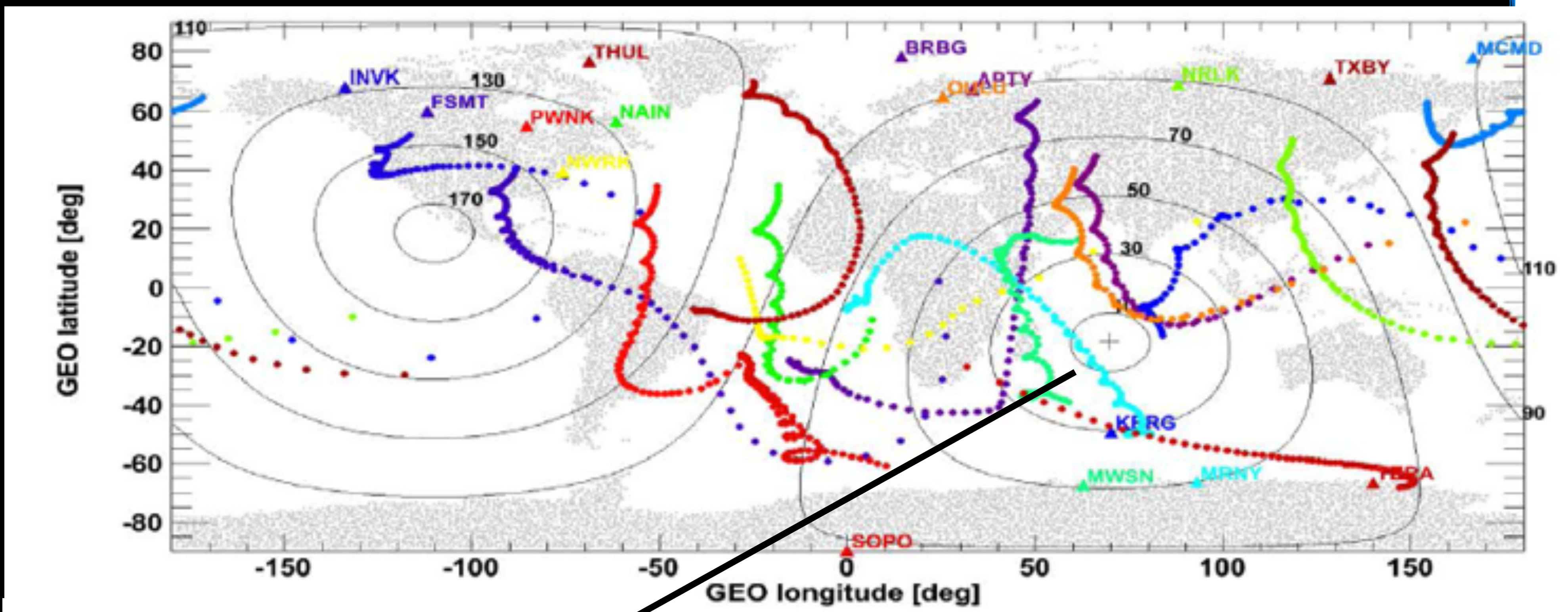
2012 May 17 GLE

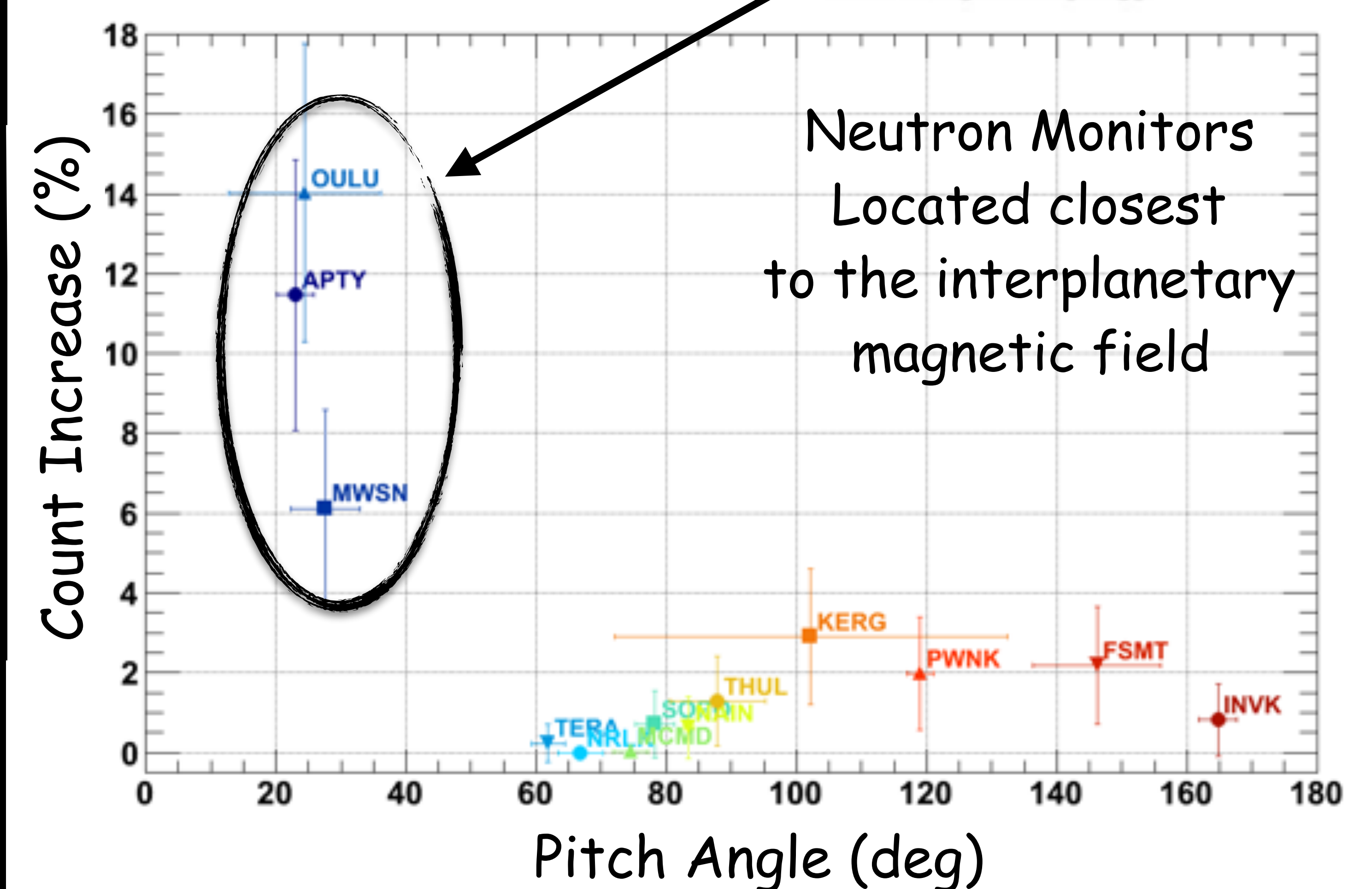


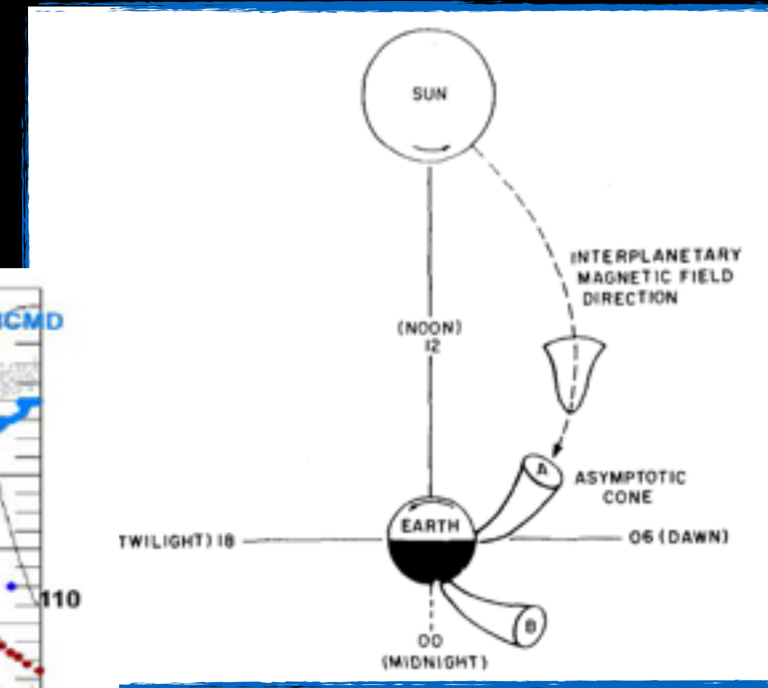
Many other neutron monitors registered the event as a ~2% increase

Highly Beamed High-Energy Event

Only stations that are magnetically connected saw the event





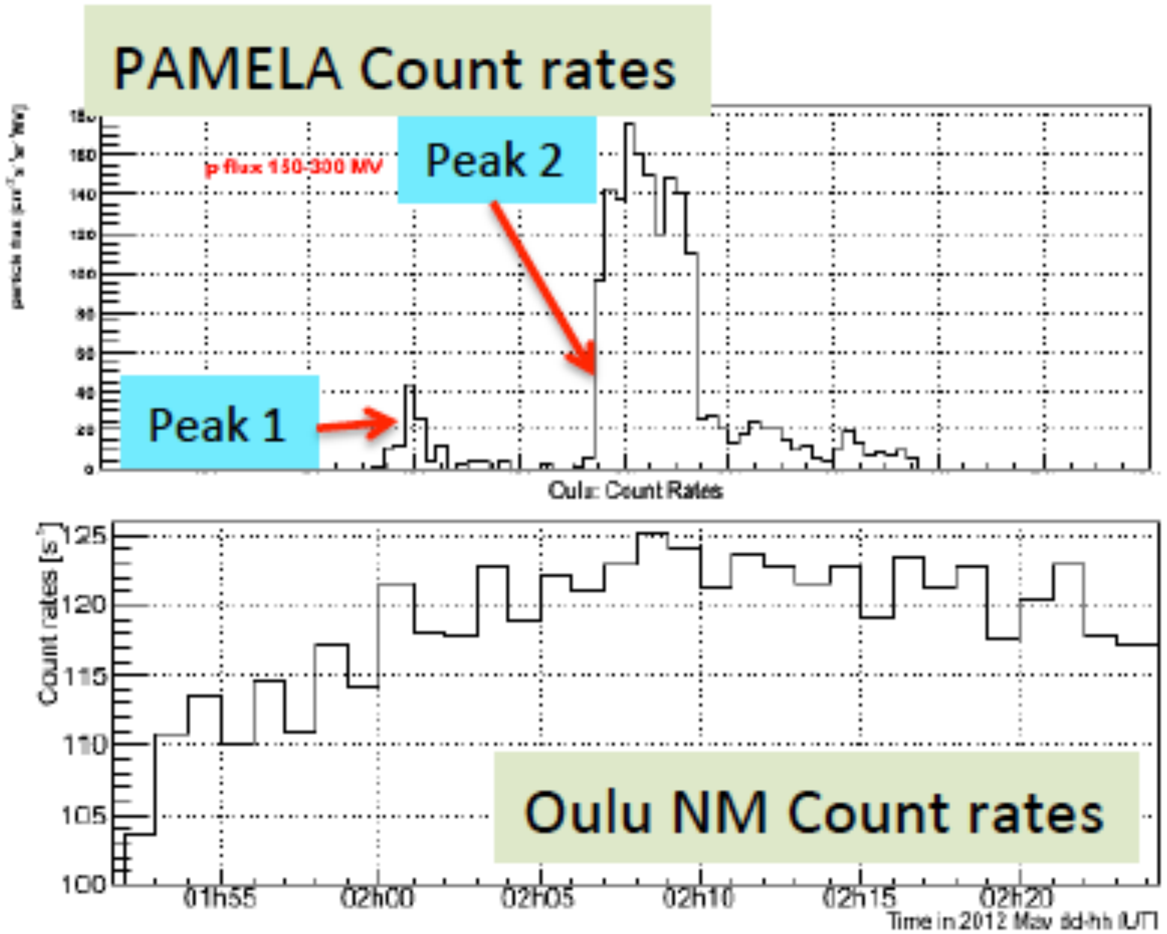


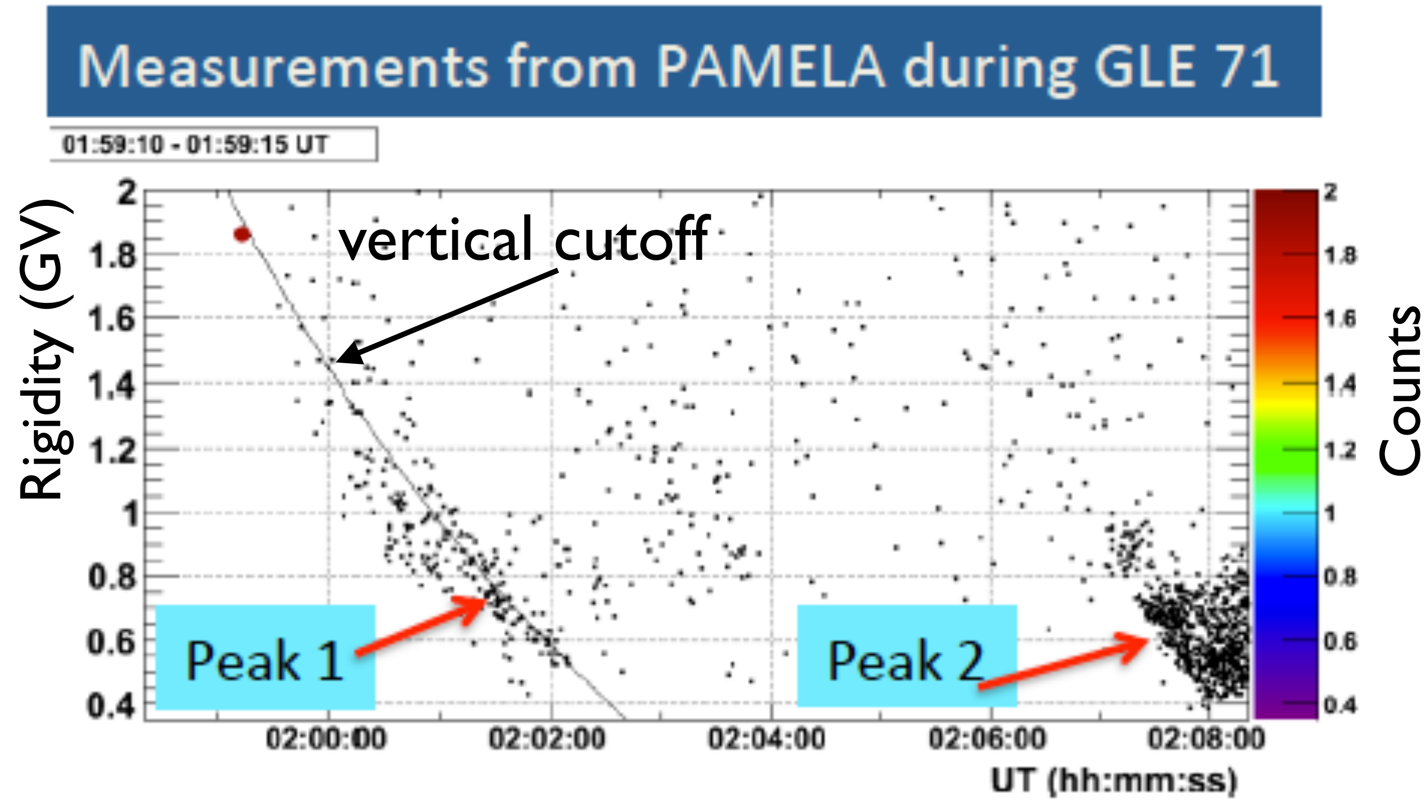
Asymptotic vertical (look) direction for each NM

— particle tracing techniques (Shea & Smart 2000)

— realistic description of the Earth's magnetosphere (Tsyganenko & Sitnov 2007)

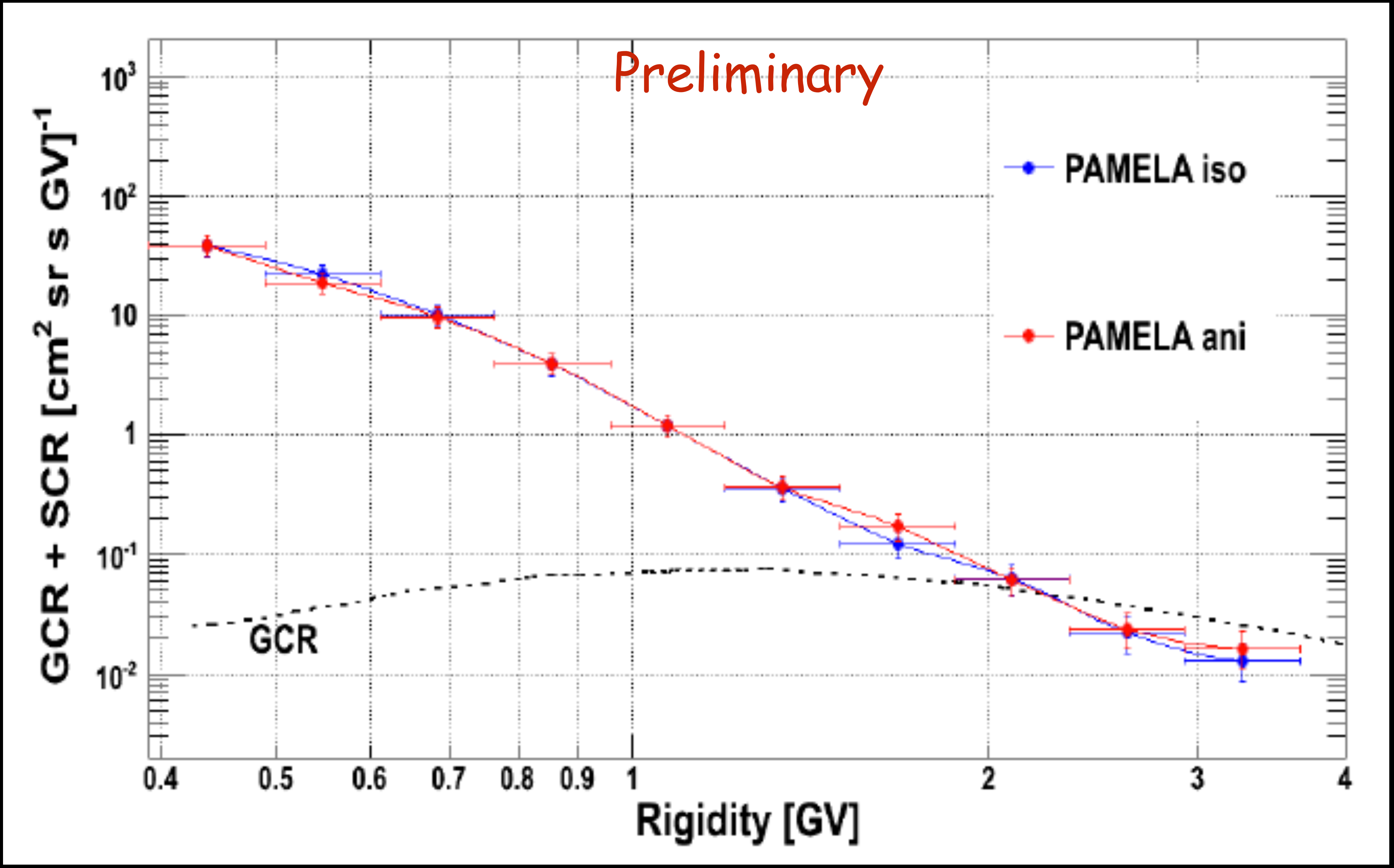
Initial PAMELA Observation





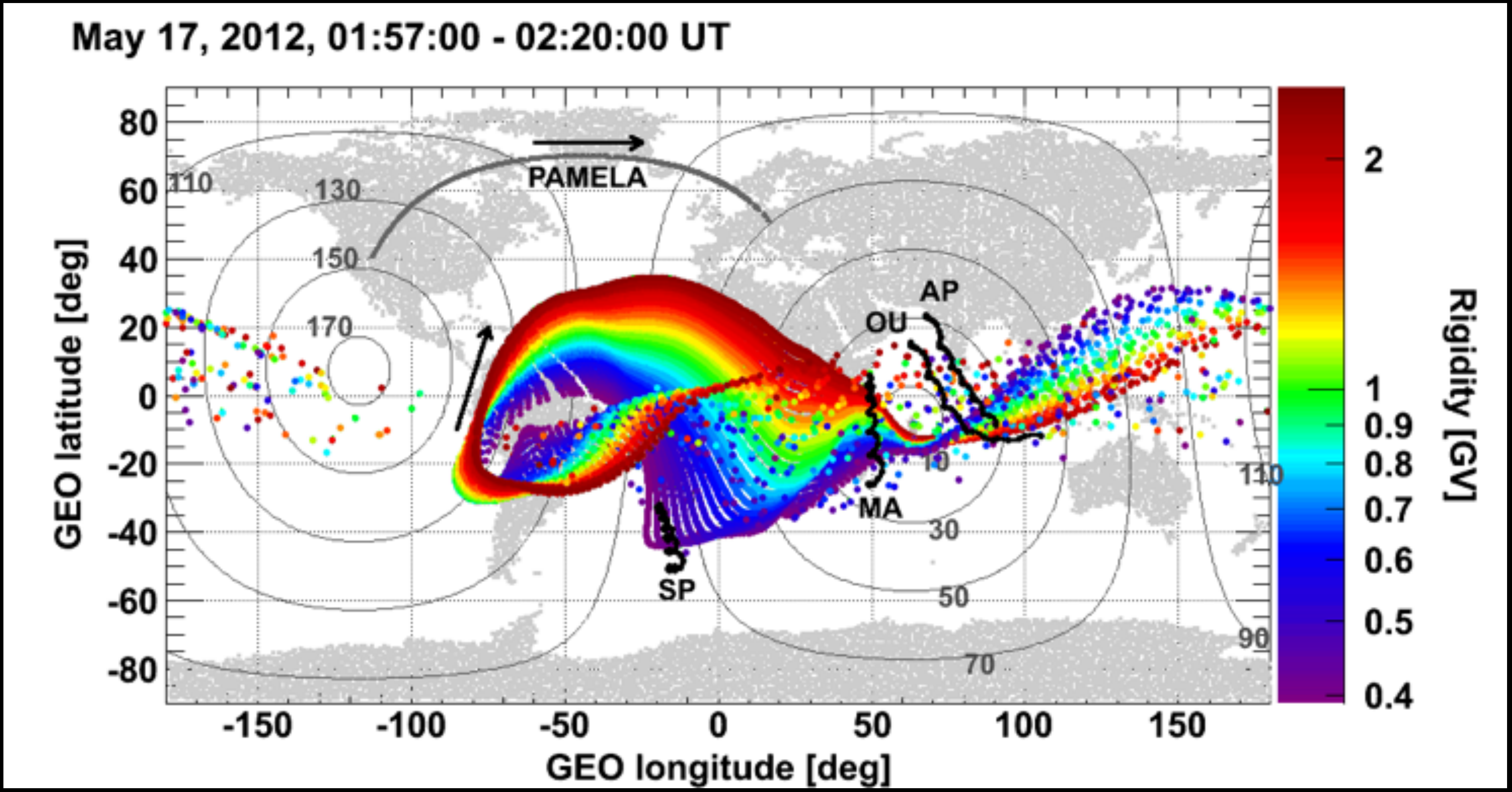
PAMELA sees two peaks.

2012 May 17



Preliminary
PAMELA iso
PAMELA ani
GCR
GCR + SCR [cm² sr s GV]⁻¹
Rigidity [GV]
10³
10²
10
1
10⁻¹
10⁻²
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4

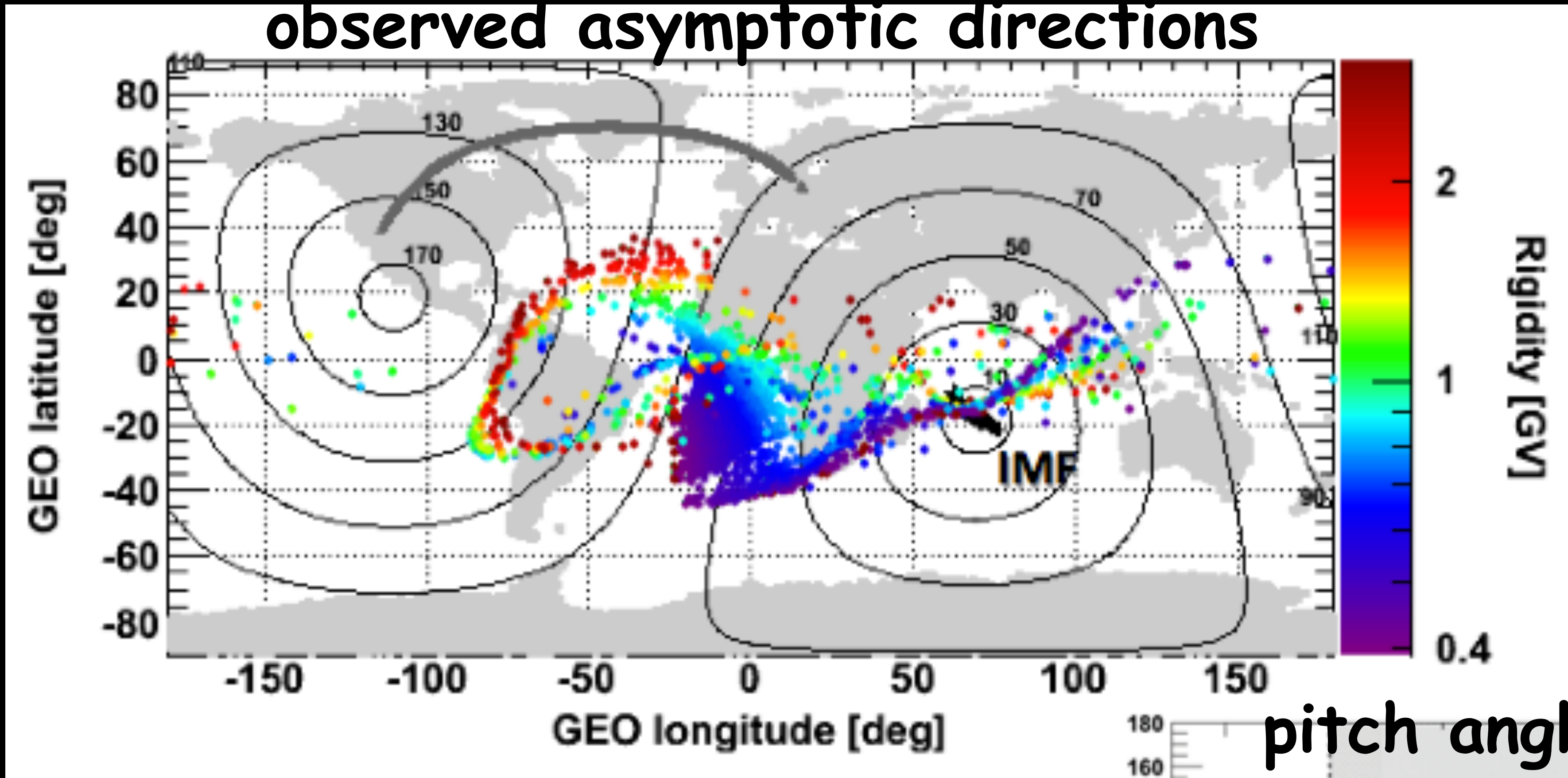
Asymptotic vertical look direction for PAMELA



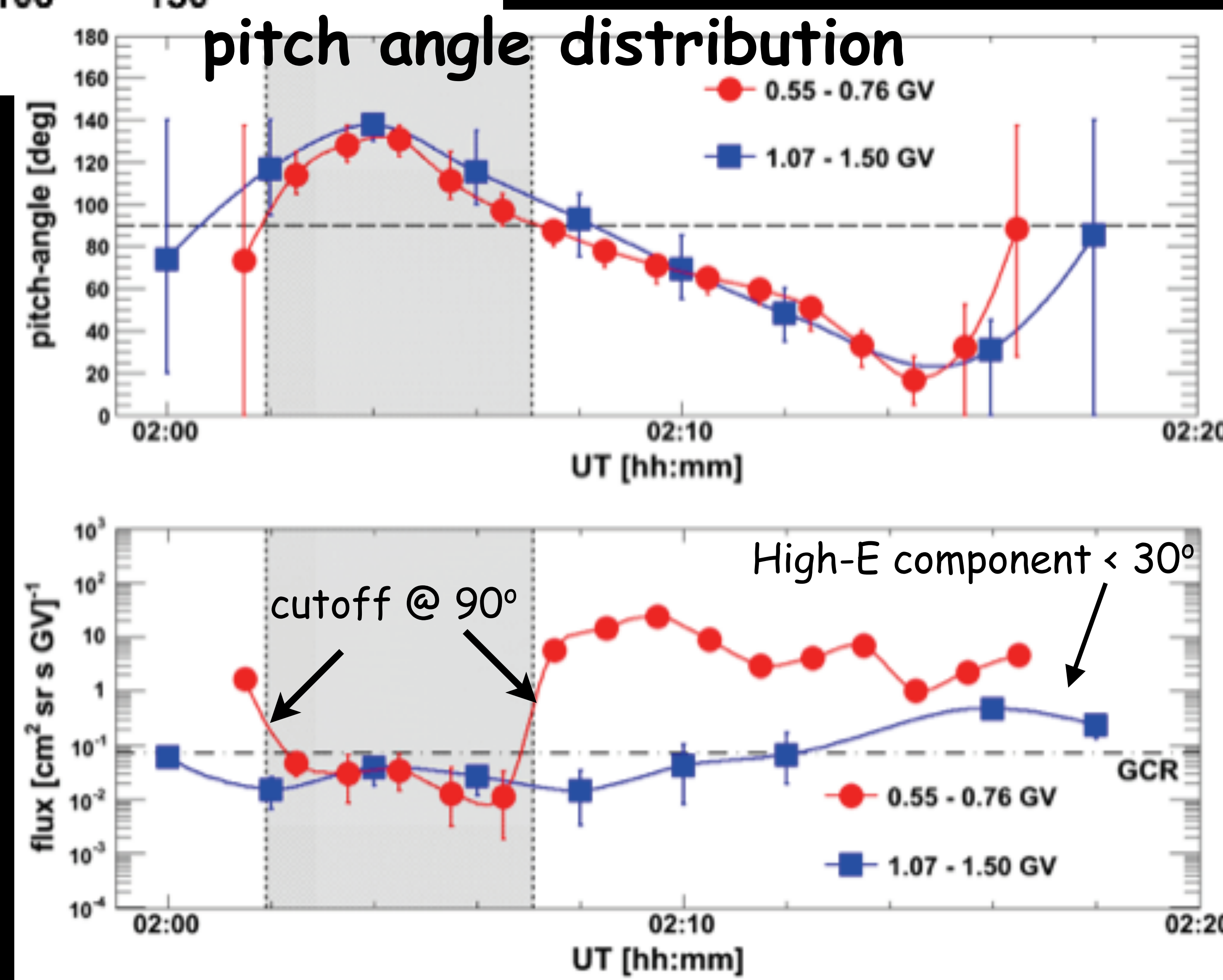
Incident trajectory
— trajectory recontruction with silicon tracking system
— particle tracing techniques.
— narrow field of view ~ 20 deg (Bruno et al. 2015)

- Calculated asymptotic directions resulting from the instrument field of view for rigidities 0.4-2.5 GV (for specific polar pass of 2012 May 17)
- While NM measure intensity for a given pitch angle, PAMELA acts as a moving observatory with sensitivity to both energy and pitch angle that depends on spacecraft location (or time). New & unprecedented view of high-energy SEPs.

-> However, identifying any evolution of the event is challenging.



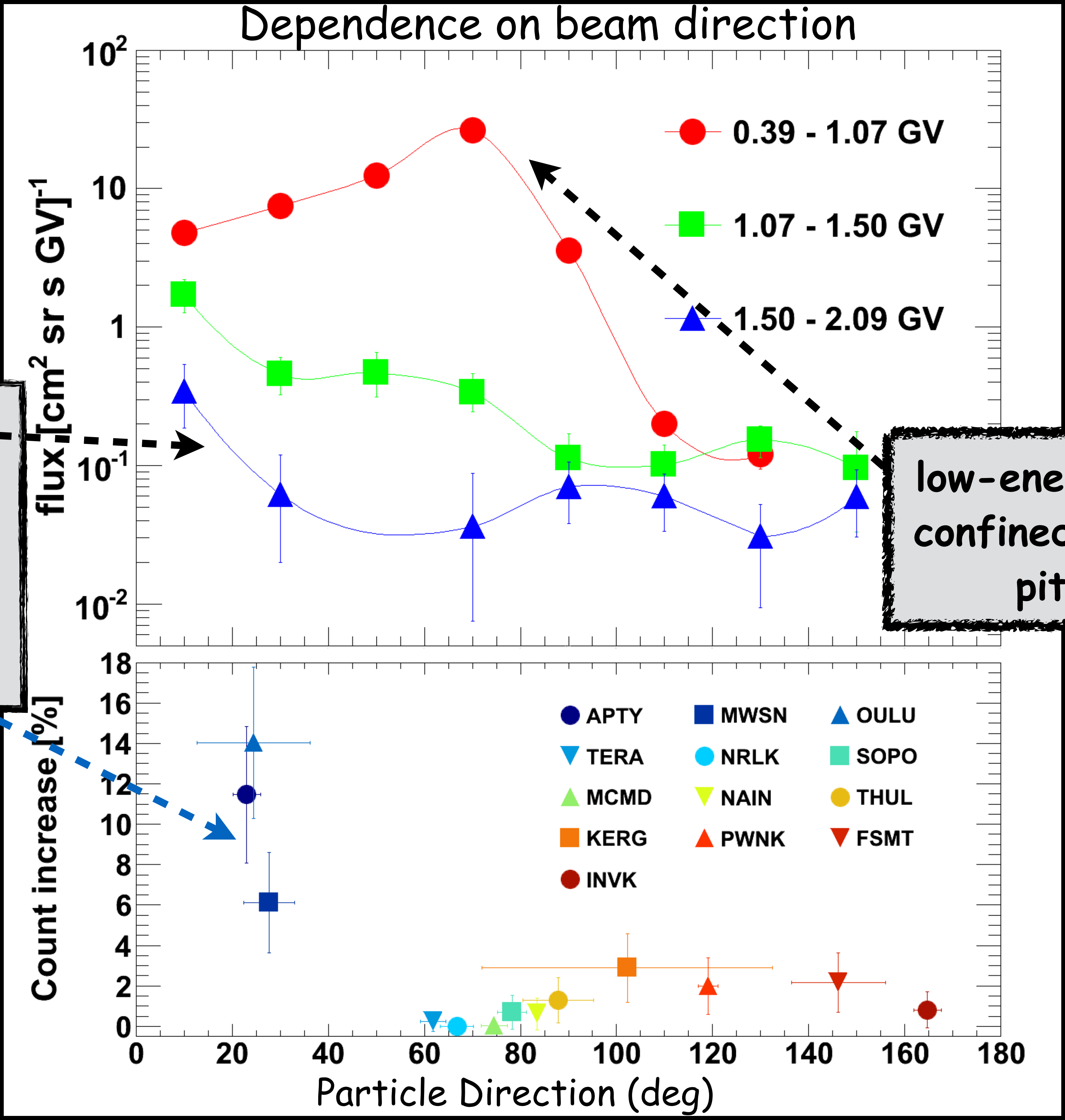
PAMELA Observations



PAMELA begins to observe the event ~10 min after onset at Apatity NM and continued to observe the event during the rising phase of the prompt emission.

Though we cannot say how the event evolves with time, it is striking that two distinct populations are present soon after the NM onset.

PAMELA Observations & A Surprise!



high-energy component with pitch angles < 30 degrees consistent with NM data

low-energy component confined to 90 degree pitch angles

Width of Beam Varies with Energy!

What's Going On?

- Typically, GLEs become isotropic w/ time.
- **First time** that we see an anisotropic field-aligned component accompanied by a broader hemispherical low-rigidity component, presumably that has undergone significant scattering (or redistribution).
  - the anisotropic nature of the ~1 GV particles is present for at least 30 min, starting from the onset (0143 UT) registered with NMs, through the 1-GV exposure of PAMELA at 0220 UT.
  - the scattered component was registered as early as 0150 UT on the leading edge of the well-connected NM signal
- The time coincidence of the two components suggests that the scattering must take place locally.

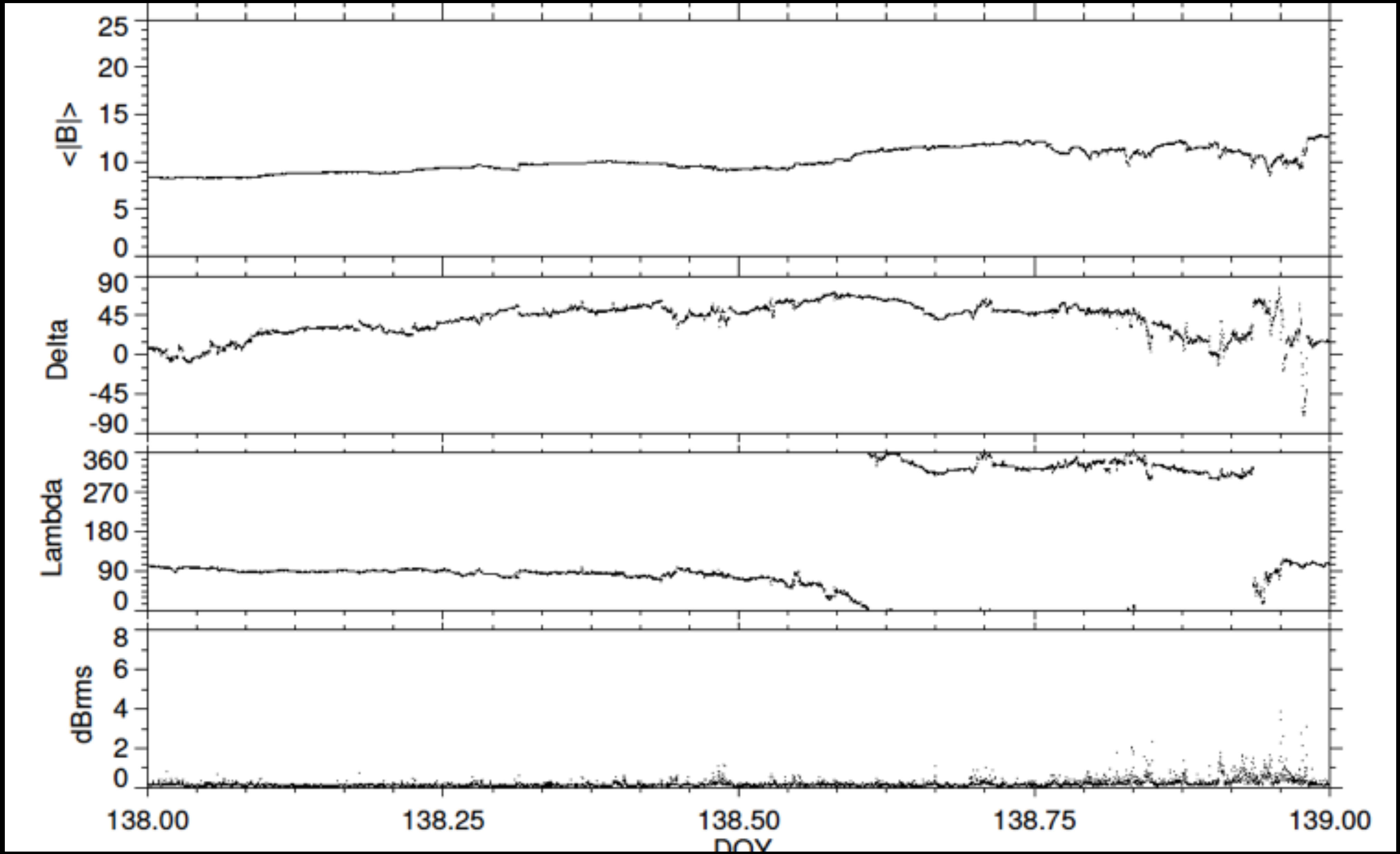
Implications

- Two populations with widely divergent pitch angle distributions @ injection would arrive at Earth with a significant time delay ⇒ **over 1/2 hour**.
- However, two populations with similar pitch angle distributions would arrive within ~10 min of each other ⇒ **well within the NM onset and PAMELA observations.**

⇒ **Must have had been released with similar pitch angles distributions**

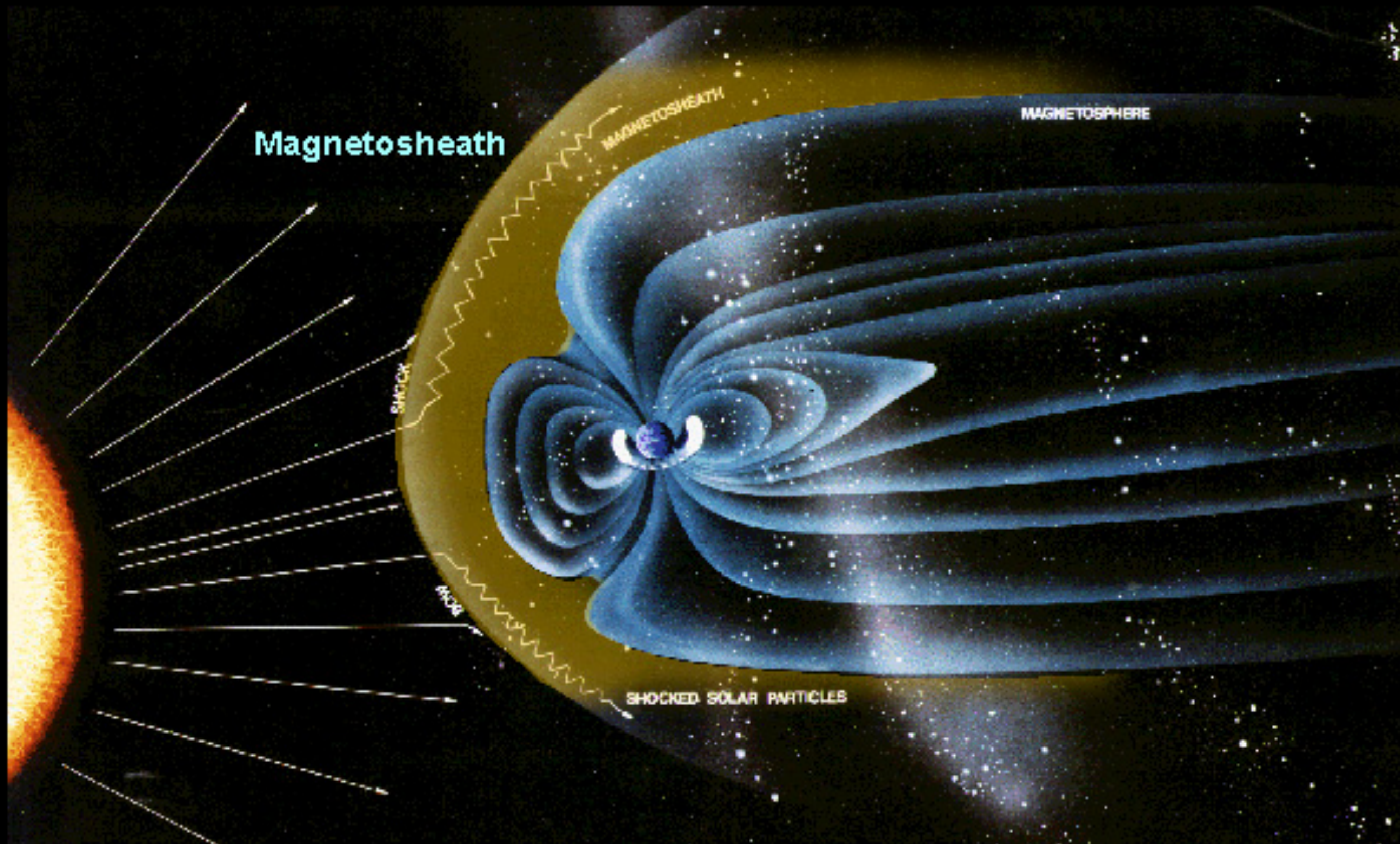
& thus the scattering of the low-energy component must occur locally.

Turbulence in the Solar Wind



1) The IMF ranged from 5 to 10 nT & the upstream rms magnetic field did not exceed 1 nT. Also, observe unusual orientation of the IMF.

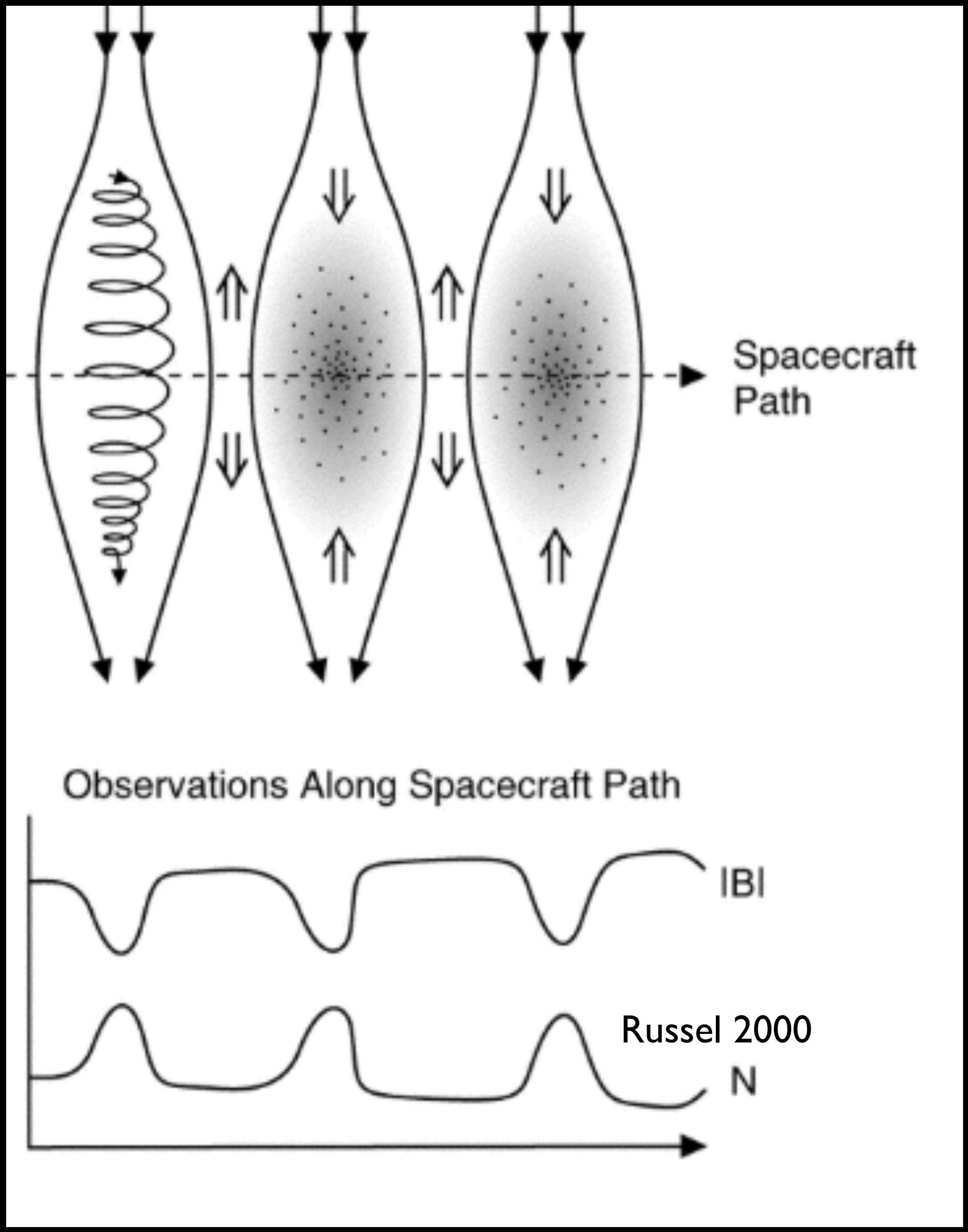
Magnetosheath Prime Candidate for Scattering



2) Bow shock is ~20 km, and so its difficult to imagine significant scattering despite the intense turbulence present in the bow shock.

3) Magnetosheath: B is intense ≳ 20 nT with large-amplitude fluctuations (≳ 50%) and is much thicker than the bow shock (~5-10R_E).

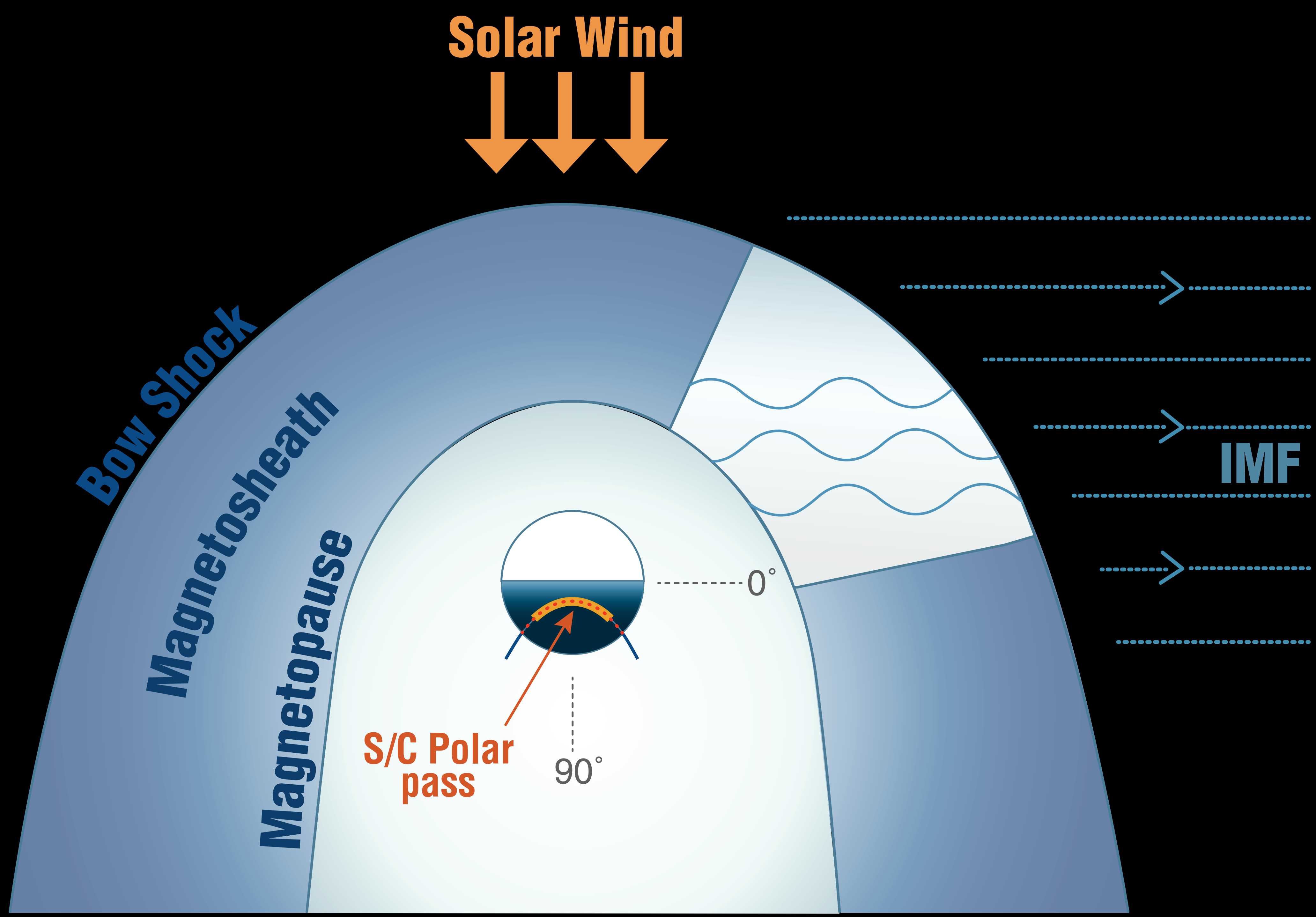
Mirror Mode Instability Fluctuations



In magnetosheath fluctuations are in the form of mirror mode, non-propagating waves which convect down the flanks as quasi-static large amplitude structures with a spatial scale in the rest frame of 1000-2000 km.

Depending on the point of entry & phase of gyration about the mean field, equal rigidity field-aligned particles would take different paths — effectively dispersing in pitch angle when they enter the quieter magnetosphere.

Working Picture



Summary of 2012 May 17th GLE

PAMELA observes distinct transport effects in the magnetosphere.

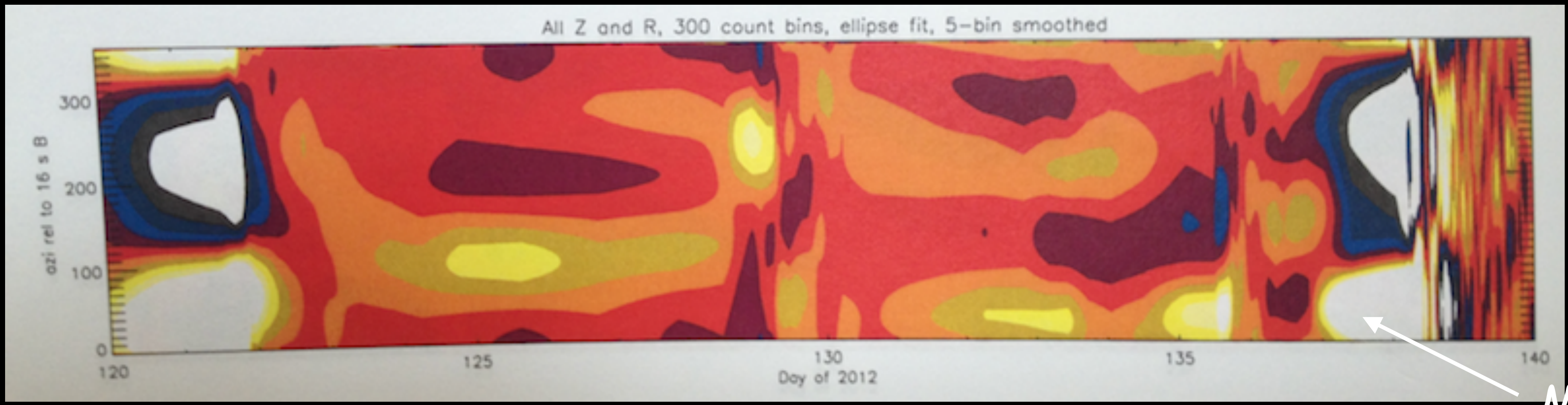
Focused on impulsive part of the GLE. Still need to model the transport details and also investigate the later phase of the GLE.

This type of analysis is only possible by measuring the direction and energy over a wide range of individual protons.

Adriani et al., ApJ 801, 2015

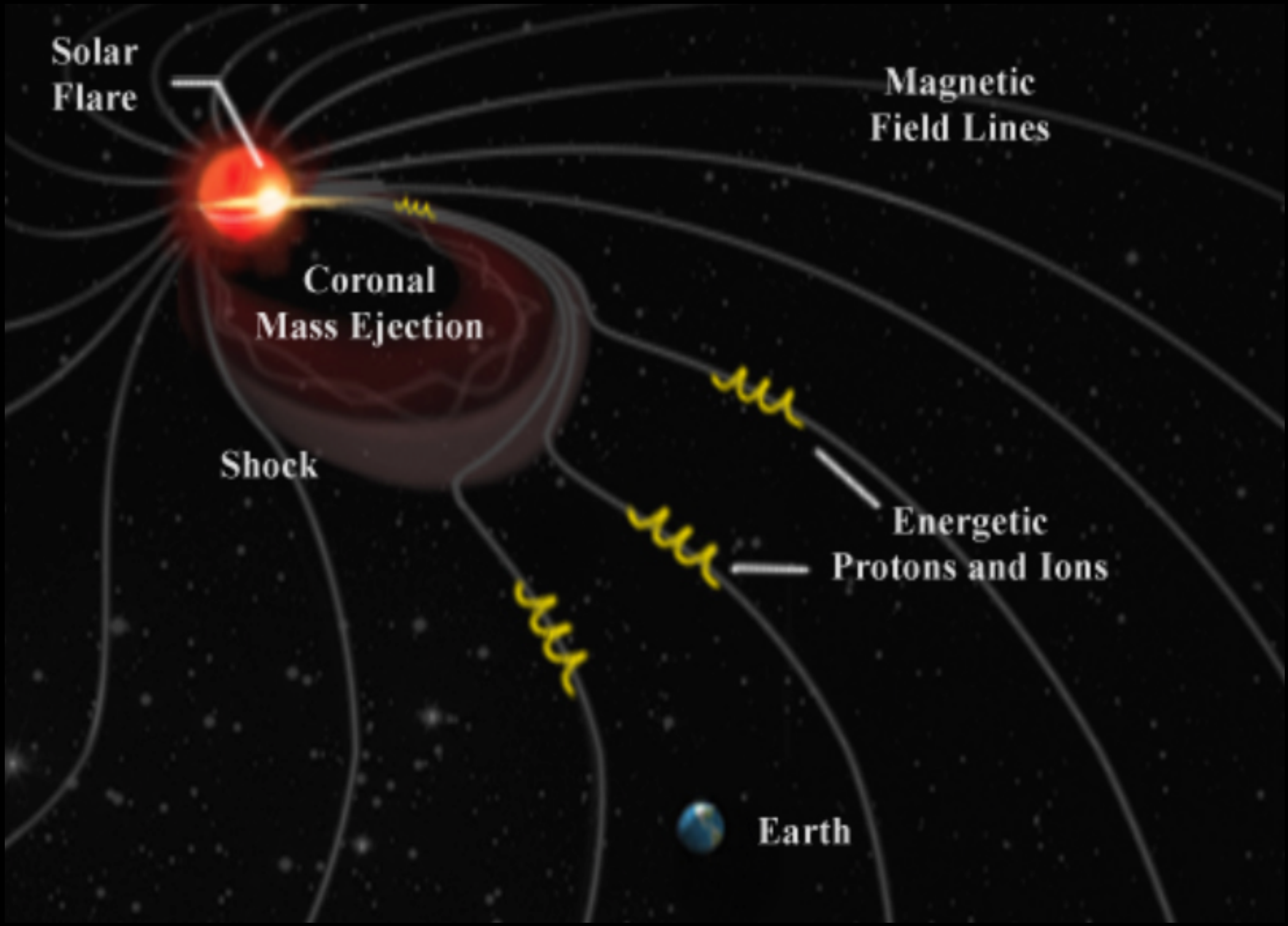
Backup Slides

ACE/SIS Anisotropy



May 17th

Acceleration & Transport



Candidates for Local Scattering

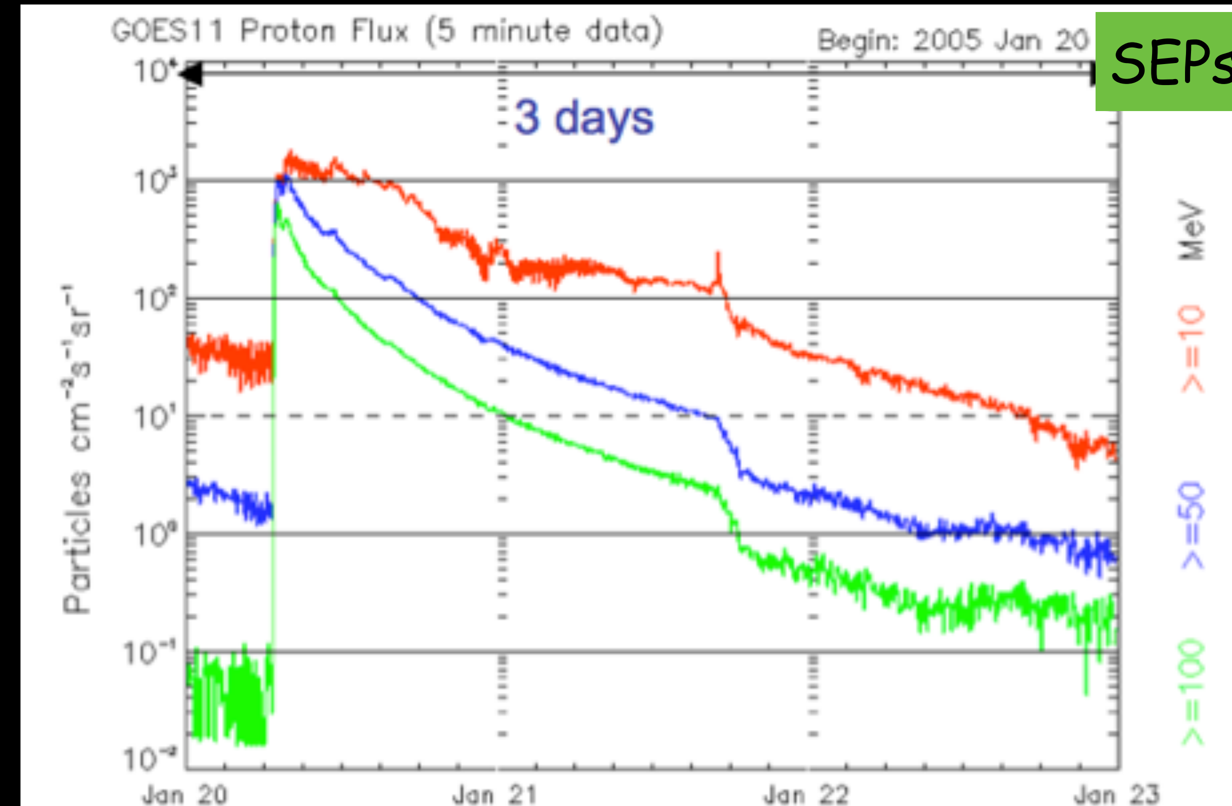
1) Upstream turbulence in the solar wind in the form of Alfvén waves,

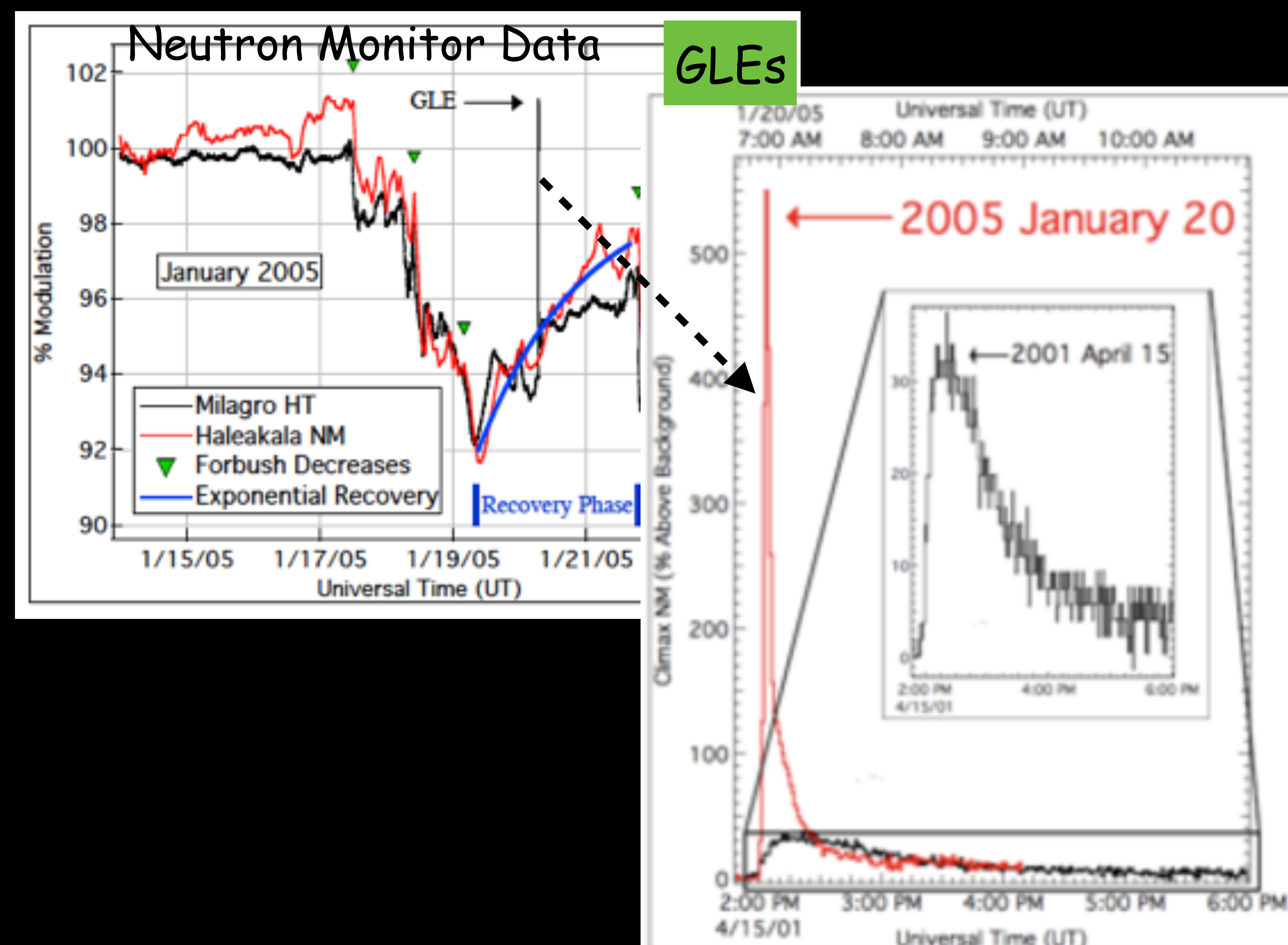
2) Intense and chaotic fields in the bow shock itself,

3) The Earth's magnetosheath

Distinct Differences Between SEPs & GLEs

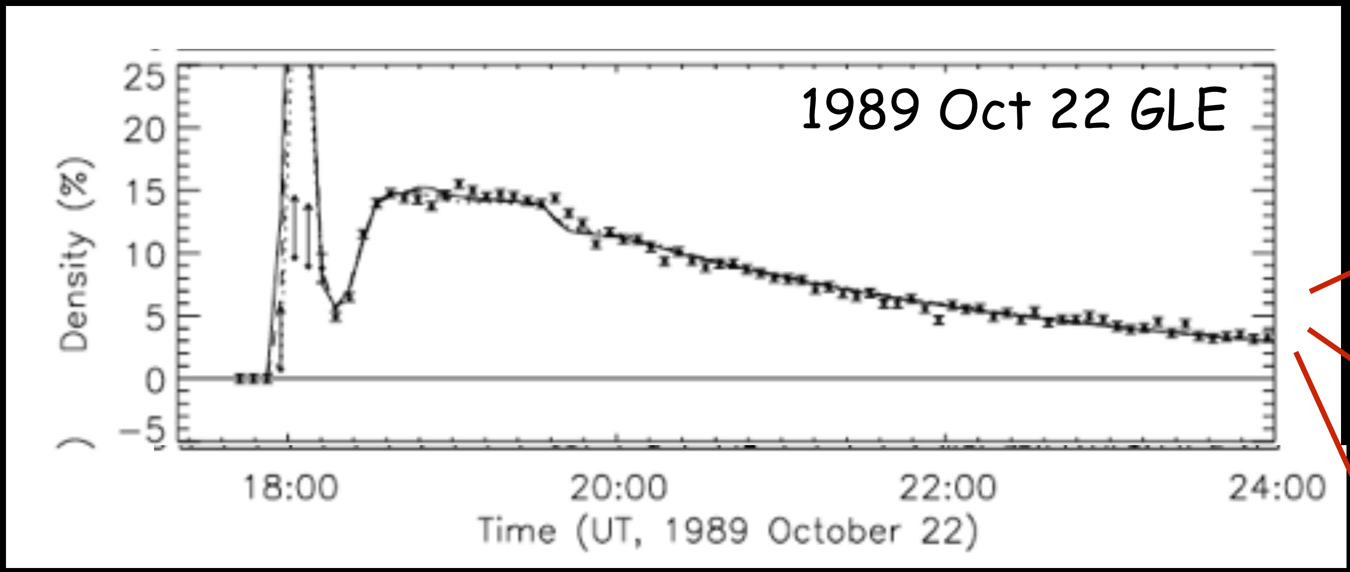
- Energy: SEP (10-100's of MeV); GLE (GeV)
- Duration: SEP : Days; GLE: Tens of minutes to few hours
- Unusual morphology suggests sometimes two separate peaks

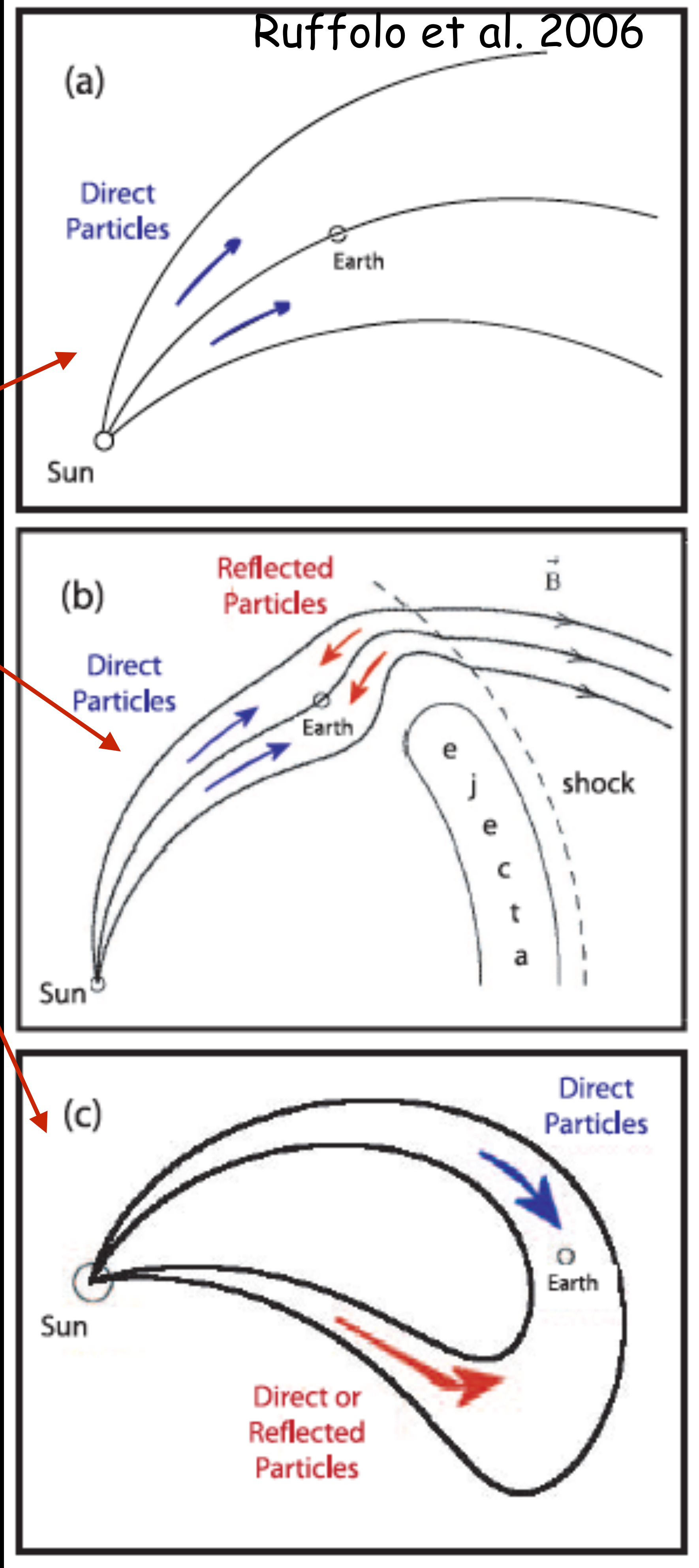


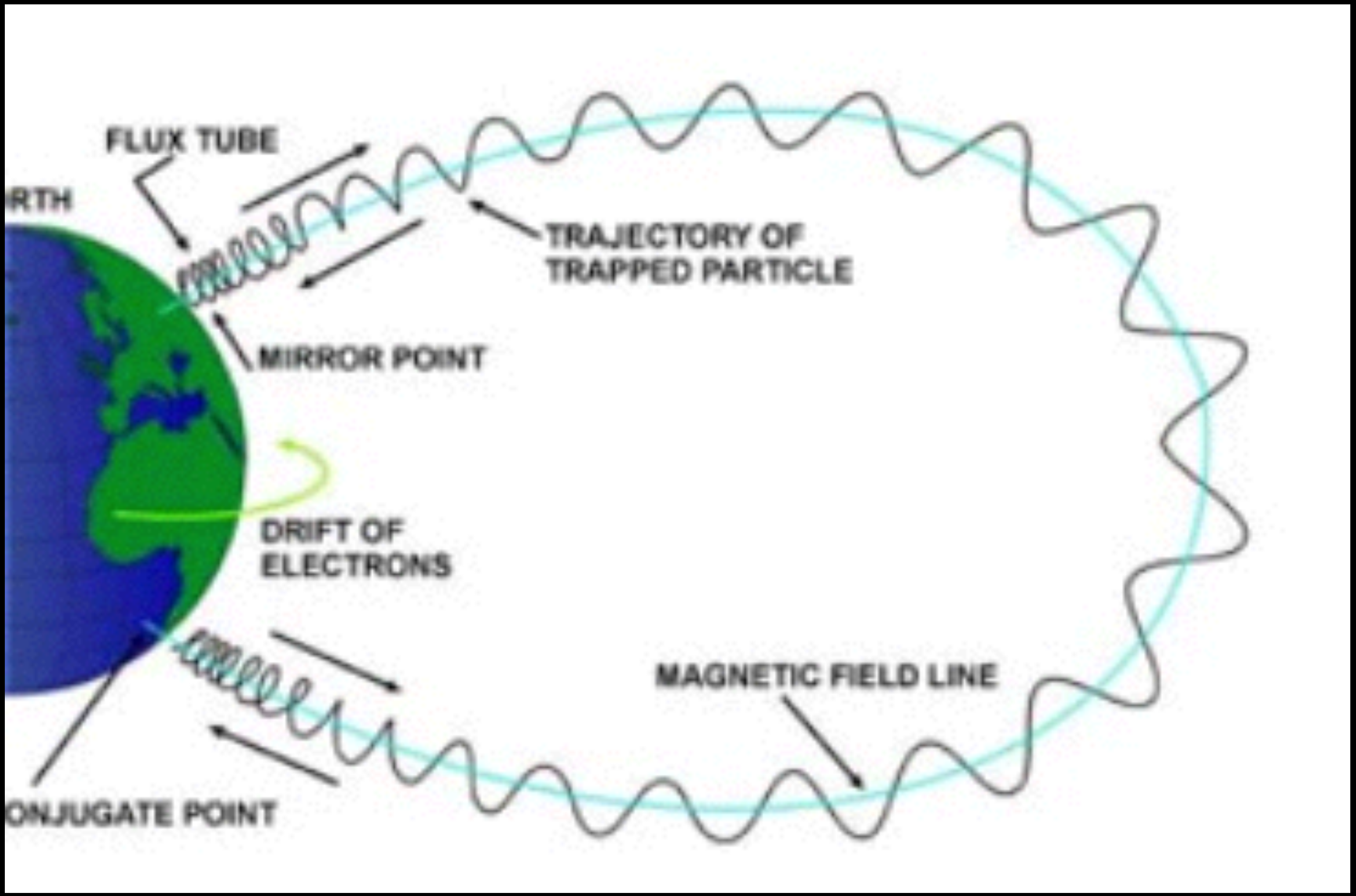


SEPs, Modulation, & Space Radiation/Hawaii 2015

Separate acceleration mechanisms of transport effect?

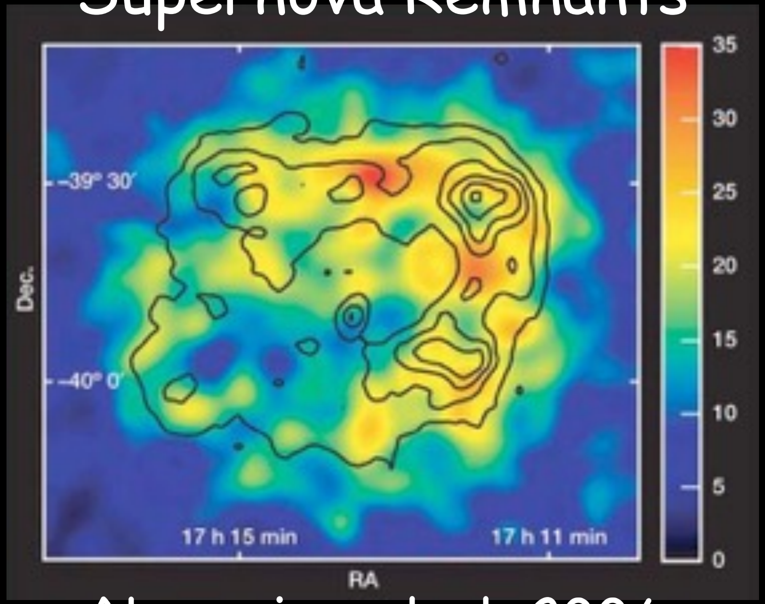




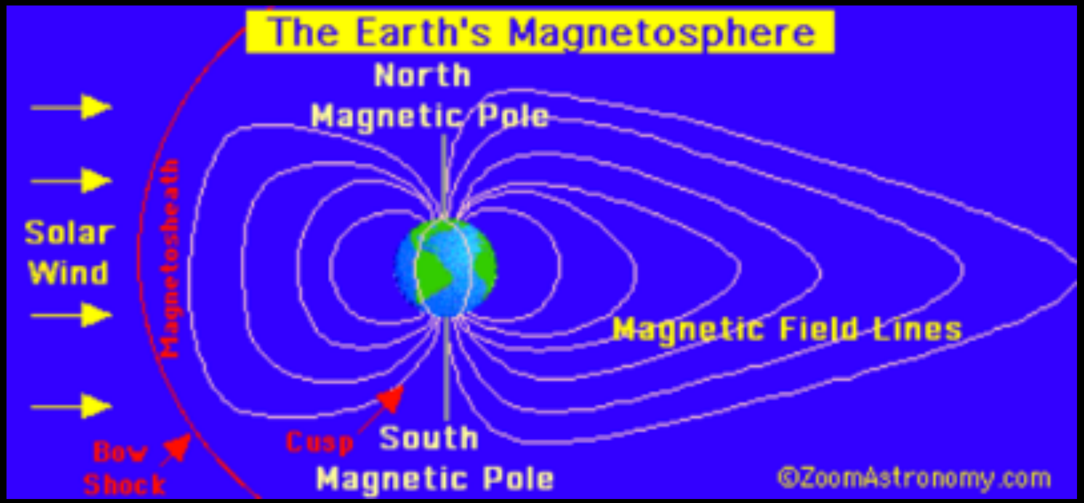

FLUX TUBE
RTH
TRAJECTORY OF
TRAPPED PARTICLE
MIRROR POINT
DRIFT OF
ELECTRONS
MAGNETIC FIELD LINE
ONJUGATE POINT

High-Energy Particle Acceleration Still a Mystery

Supernova Remnants

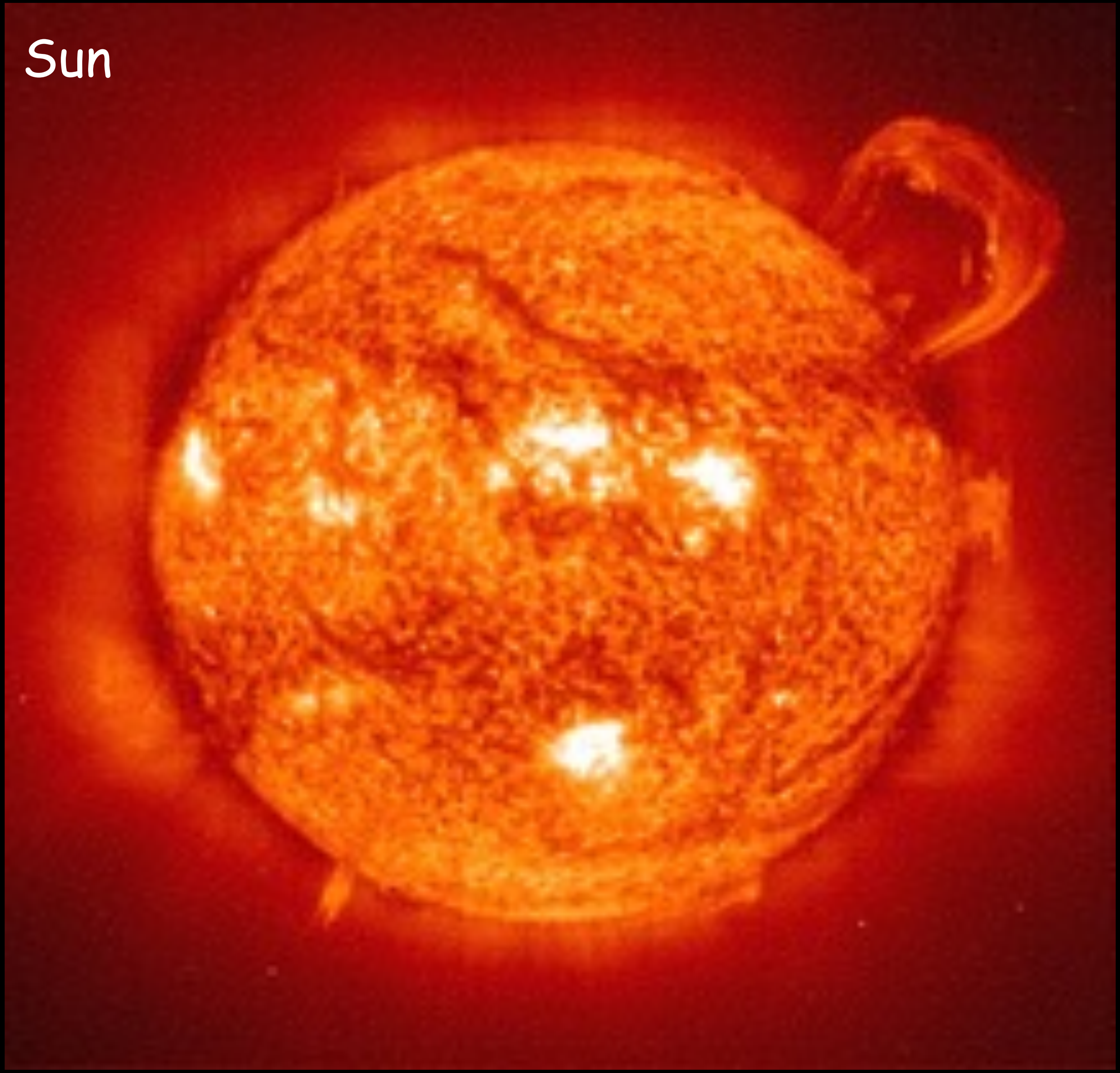


Aharonian et al. 2004



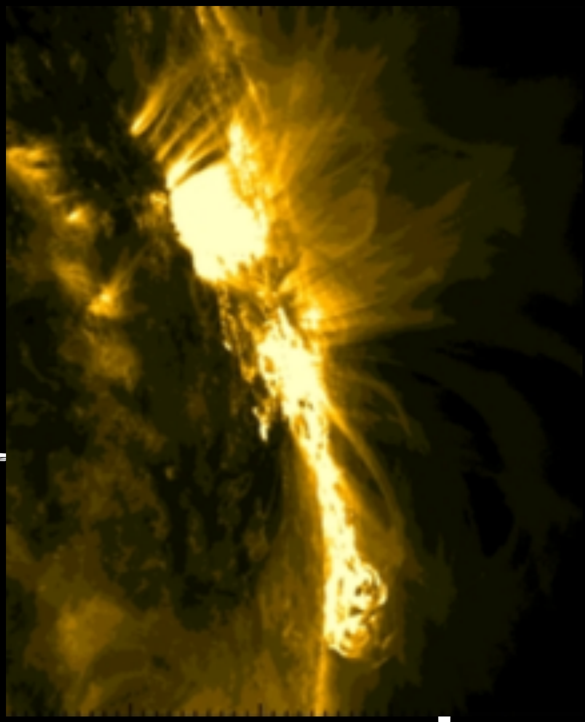
- Distant galactic sources— particles reach extreme energies but cannot see acceleration in progress — too far to observe in detail
- Near Earth — close by but processes are do not accelerate to extreme energies.
- The Sun — produce particles with energies approaching the speed of light & we can watch it happen!

High-Energy Particle Acceleration Still a Mystery



The Sun — produce particles with energies approaching the speed of light & we can watch it happen!

Rare Extreme Energy Events : Ground Level Enhancements



- Solar events with particle energies approaching the speed of light are known as Ground Level Enhancements (GLEs)
- Rare (~1 per year!) reaching such high energies that can be observed by ground-based instruments (unlike typical Solar Energetic Particles (SEPs))
- Detecting fast particle is challenging — Need large instruments to register these rare events.