Outstanding questions around the energy of EMIC wave driven electron precipitation

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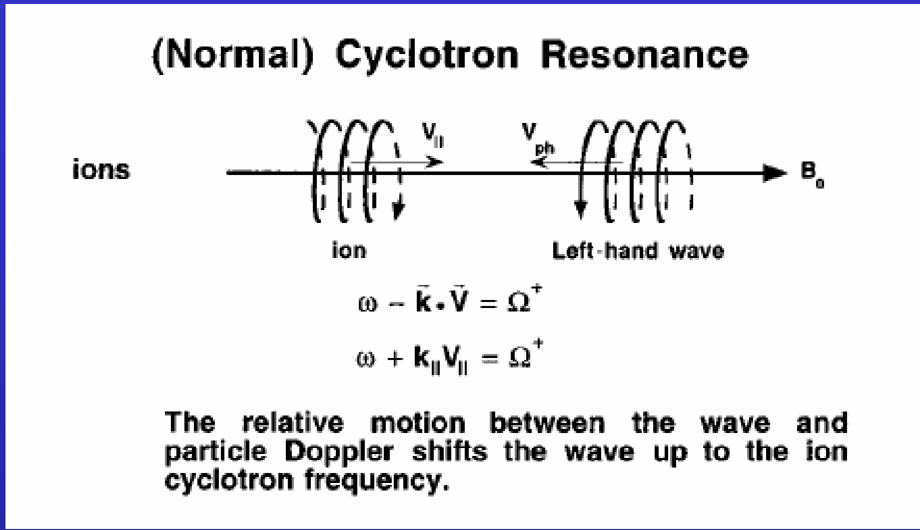
AGU Chapman Conference
Cascais, Portugal
Longshot and Bogey (Hotel Quinta da Marinha)
1030-1050, Wednesday 7 March 2018

Cyclotron Resonance for EMIC waves



"Normal" cyclotron resonance occurs between counter-streaming waves and particles.

For the case of an ion-cyclotron wave like an EMIC wave, the normal resonance will be with protons with 10's to 100's keV energy.

Plots from Tsurutani and Lakhina (1997), Rev. Geophys., doi:10.1029/97RG02200.

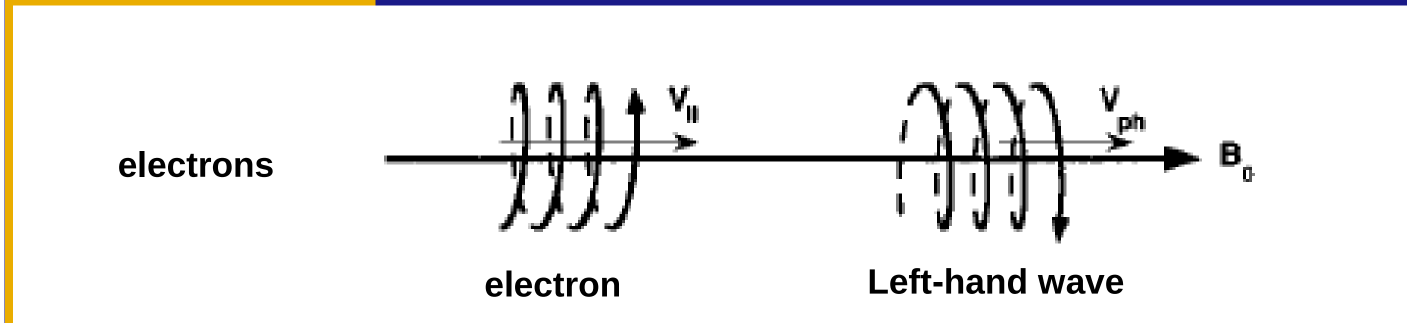


Figure 11. Schematic illustrating anomalous cyclotron resonance between electromagnetic circularly polarized waves and

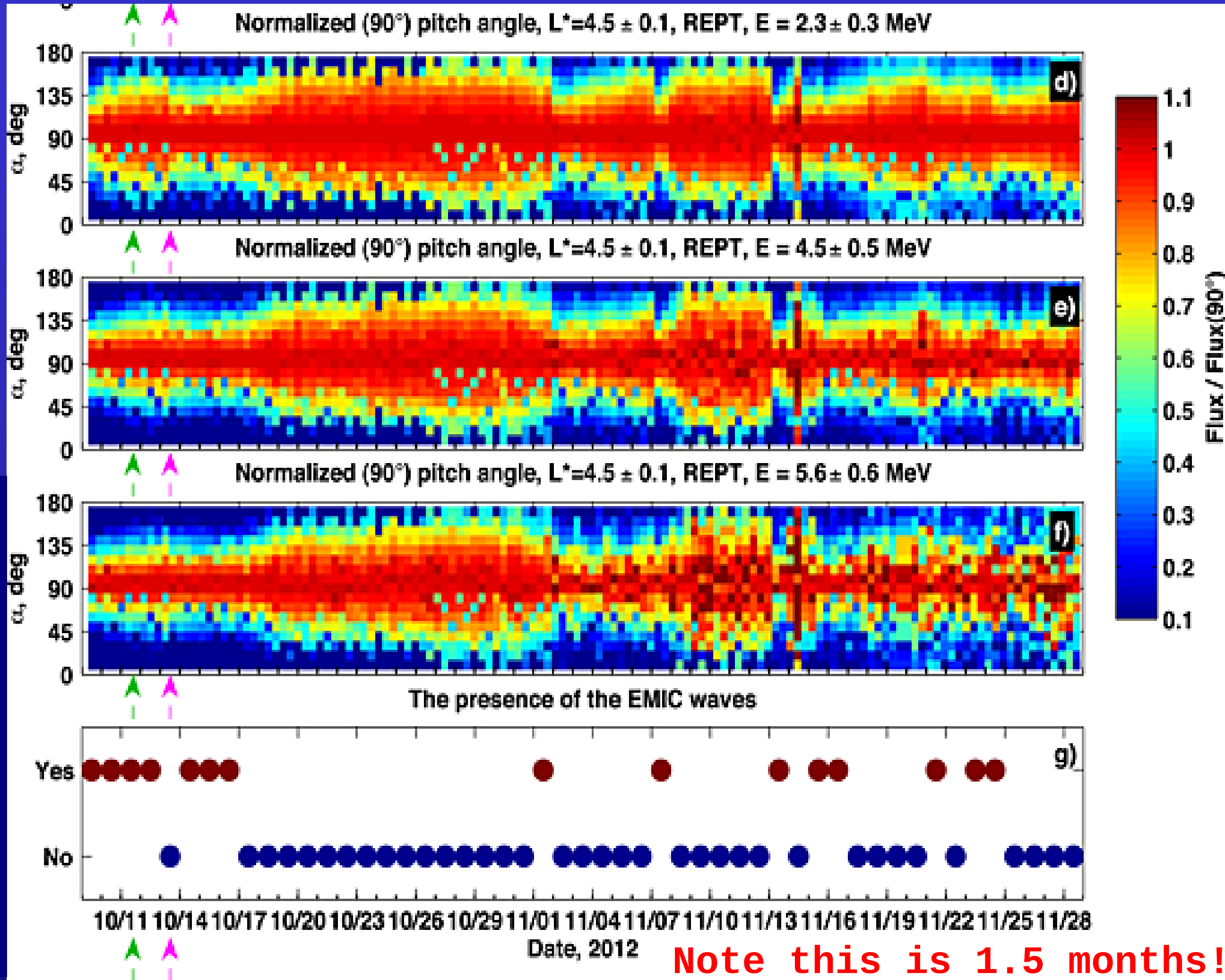
"Anomalous" cyclotron resonance occurs when particles overtake the wave.

For the case of an EMIC wave, anomalous resonance are thought to be important for scattering relativistic electrons (~1 MeV).

Thorne and Kennel (1971) first suggested that EMIC wave scattering was a major loss mechanism for relativistic electrons.

EMIC Waves – very significant player?

From: Usanovaet et al. (2014), *Geophys. Res. Lett.*, 41, doi:10.1029/ 2013GL059024.

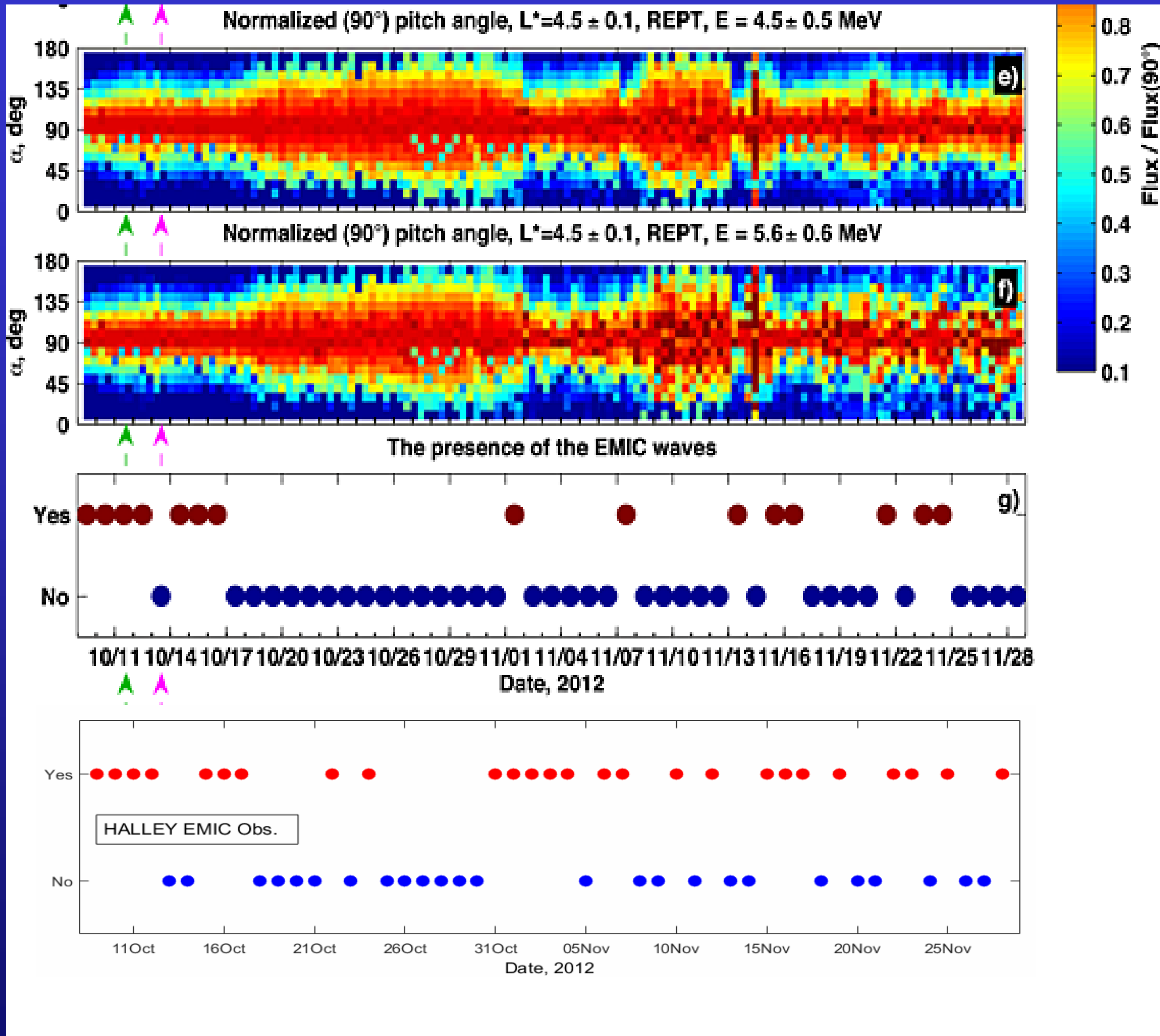


Maria Usanova reported that over some long time periods EMIC waves were observed on the ground and RBSP saw decreases in the ultra-relativistic trapped fluxes (but not for 90° pitch angles).

Note no actual precipitation was observed at these times.

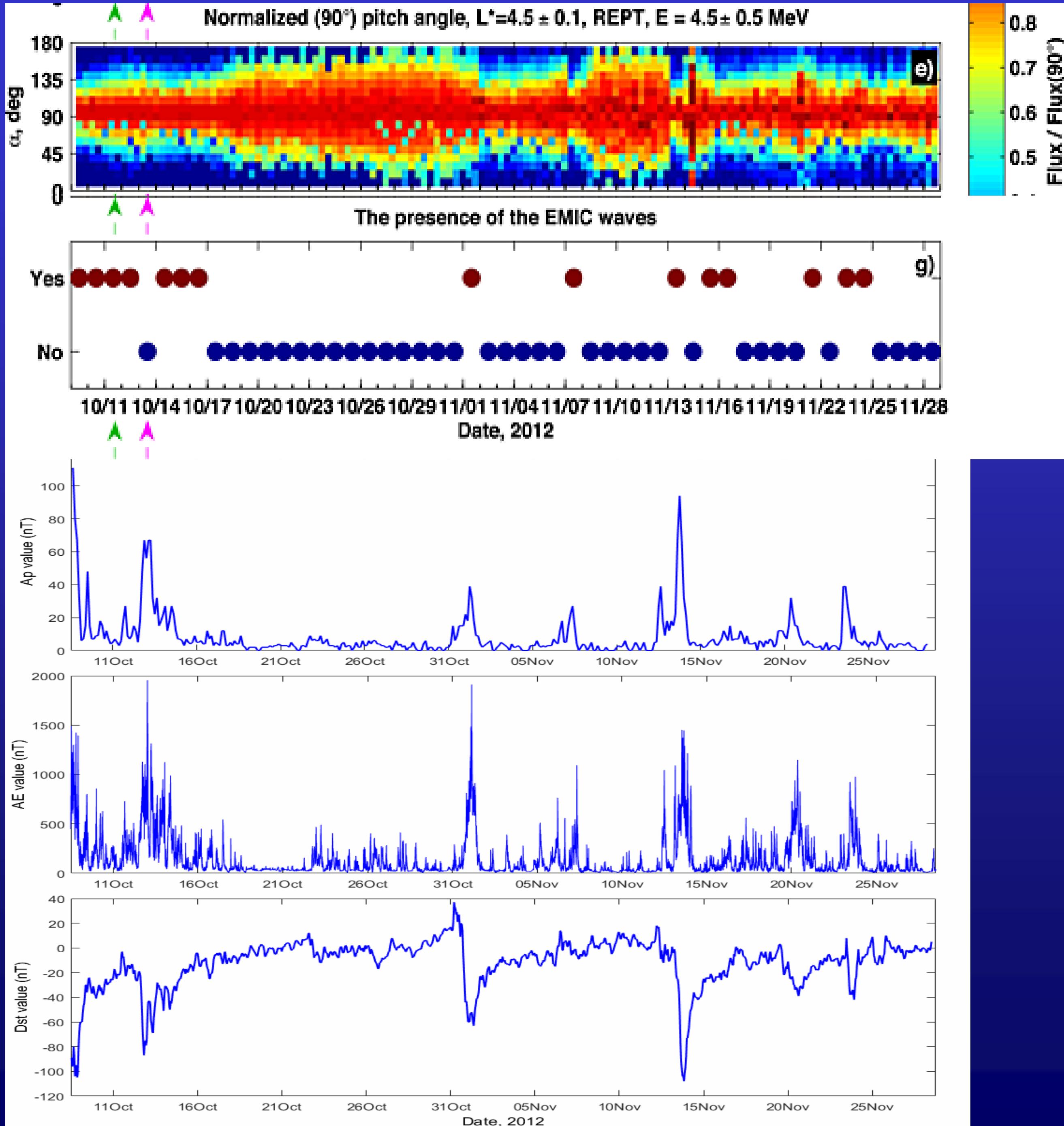
To quote: this figure "demonstrates an extremely clear correlation and connection between rapid changes in ultrarelativistic pitch angle distributions and the occurrence of EMIC waves. It provides good evidence that EMIC waves can generate bite-outs in flux at low pitch angles, which can last for extended intervals."

EMIC Waves – very significant player?



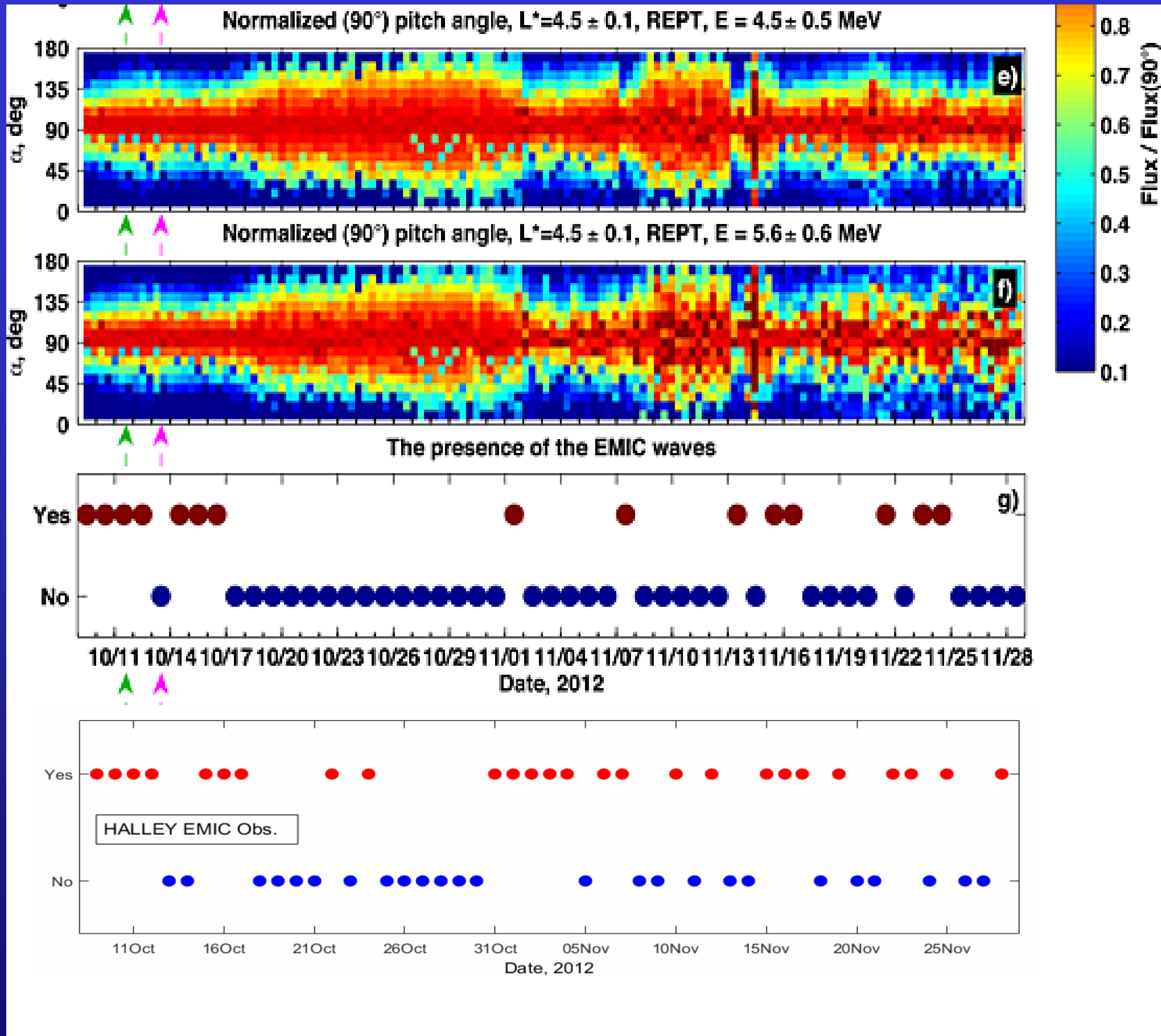
Doing the same check with the magnetometer at Halley produces quite a different picture.

EMIC Waves – very significant player?



You might argue (and last year I did at a talk at URSI) that at least some of these notches in the very relativistic electron flux distributions correlate well with storms, as much as those CARISMA EMIC observations.

EMIC Waves – very significant player?



However, Maria argues she was able to check the CARISMA array to try and link the wave to the right L-shell, which is not the case for the Halley observations.

However - that was not a one off!

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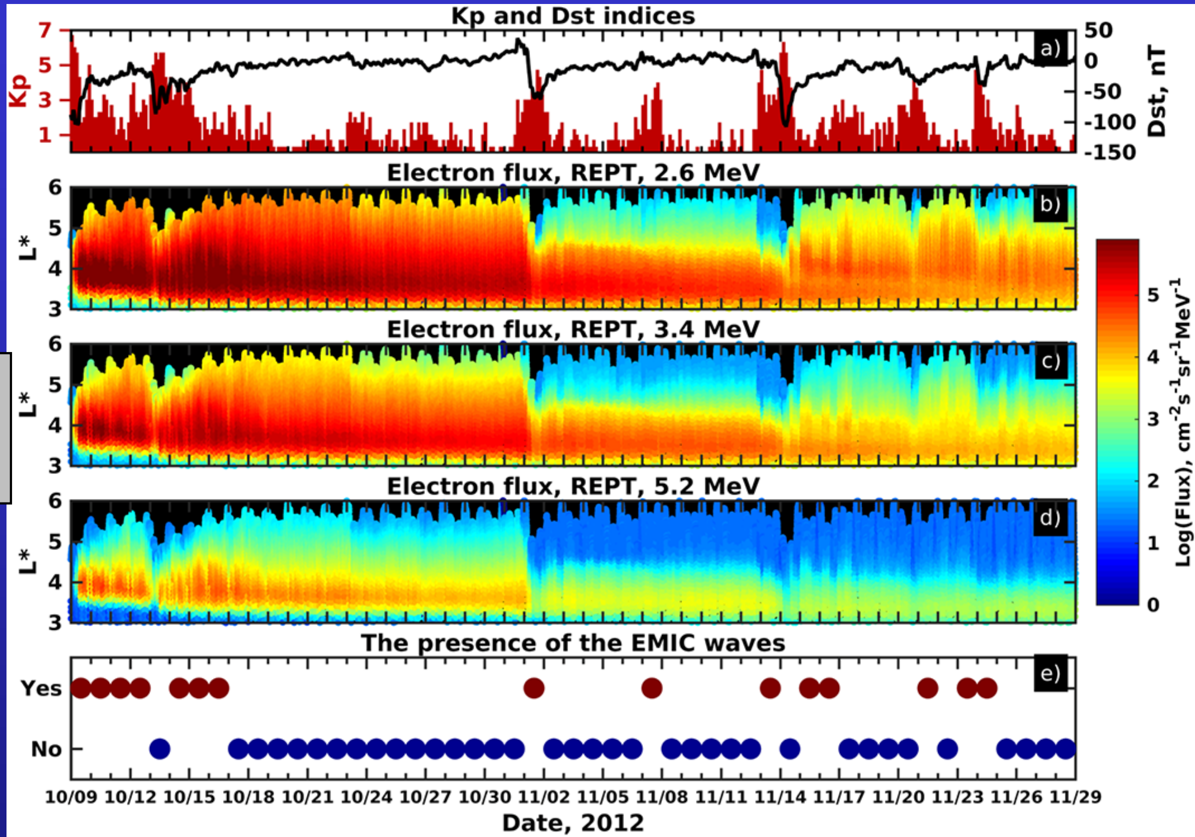


From: Aseev el al. (2017), *J. Geophys. Res.*, 122, doi:10.1002/2017JA024485.

And there are more and more examples of these sort of link appearing in the literature (plus probably more will be presented at this meeting).

So then I tried to look for evidence of this impact for myself. I looked at the RBSP "quick look" data for a number of times I knew EMIC-waves had been seen.

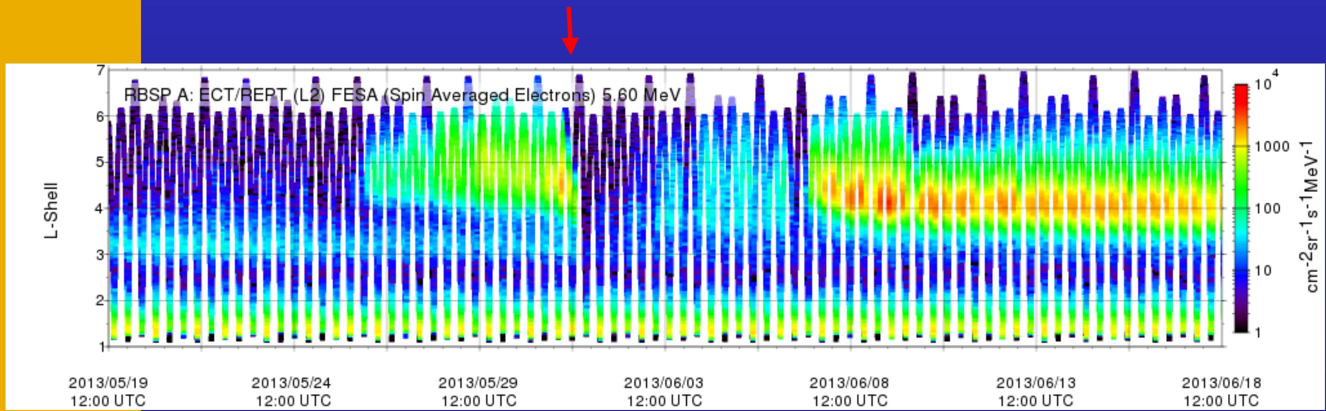
And when I tried to look for myself - I

<u>**EMIC event from 21:15-22:00 UT on 31 May 2013**</u>

Event from: Clilverd et al. (2015), *J. Geophys. Res.*, 120, doi:10.1002/2015JA021090.

Evidence of sub-MeV precipitation from POES

Evidence of EMIC waves from the SCM at Halley



RBSP 5.6 MeV trapped electron fluxes

Decrease in ultra relativistic electrons down to very low *L* (about *L*=3). Looks like that occurs at **05:30UT on 1 June 2013**, which is closeish to the ground-based wave activity.

decrease seen a bit <u>after</u> the wave event. **close enough in time?**

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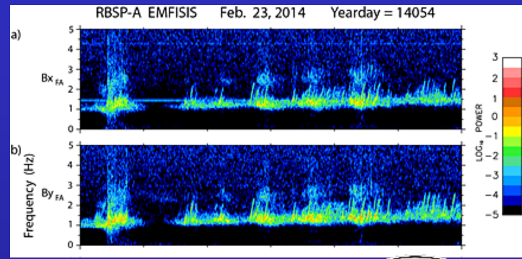
And when I tried to look for myself - II

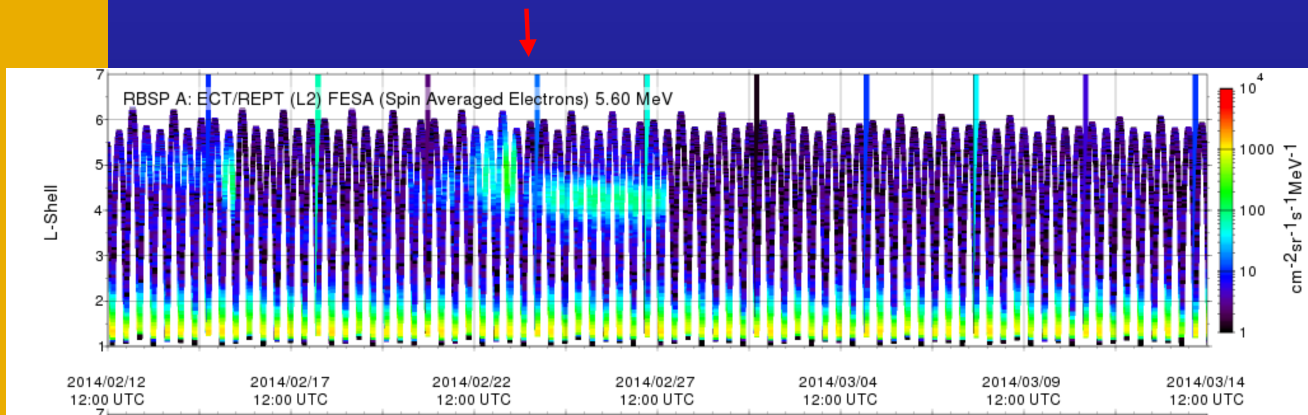
EMIC wave event on 23 February 2014

Event from: Engerbreton et al. (2015), *J. Geophys. Res.*, 120, doi:10.1002/2015JA021227.

Waves seen from **2-8 UT** on RBSP, through to 11UT in ground based data. Unusually high peak intensity on ground at ~7:30-8:00 UT on 23 Feb 2013.

No known electron precipitation observations for this event.





RBSP 5.6 MeV trapped electron fluxes

Ultra relativistic flux decrease at **~18:33UT** on 23 Feb 2014 (which quickly recovers).

decrease seen a bit after the wave event. **close enough in time?**

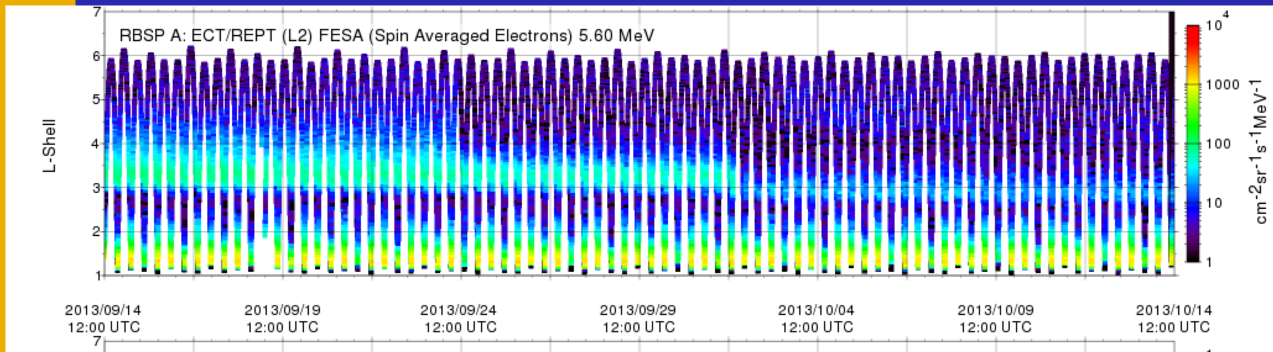
And when I tried to look for myself - III

EMIC wave event on 24 September 2013

Event from: Rodger et al. (2015), *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL066581.

Waves seen on RBSP **16:41-17:20UT**

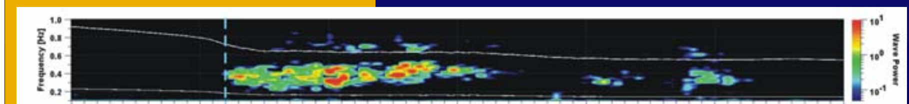
Evidence of sub-MeV precipitation from POES
& confirmation of precipitation from AARDDVARK



RBSP 5.6 MeV trapped electron fluxes

Dropout seen in RBSP ultra relativistic fluxes, from **12:30UT** on 24 September 2013, down to about *L*=3.8.

decrease seen a bit <u>before</u> the wave event. **close enough in time?**



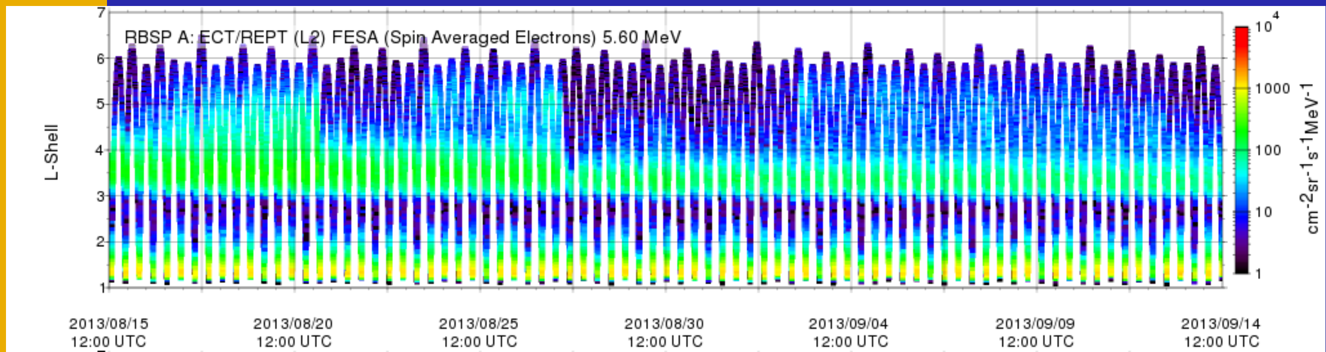
And when I tried to look for myself - IV

EMIC wave event on 27 August 2013

Event from: Rodger et al. (2015), *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL066581.

Waves seen on RBSP at about **15:52 and 16:52 UT**

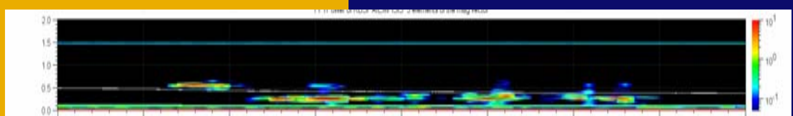
Evidence of sub-MeV precipitation from POES



RBSP 5.6 MeV trapped electron fluxes

Dropout seen in RBSP ultra relativistic fluxes, from **~19:50UT** on 27 August 2013, down to about L=4.0.

decrease seen a bit after the wave event. **close enough in time?**



And when I tried to look for myself - V

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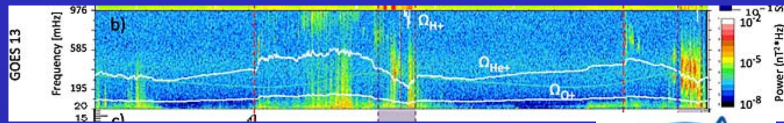
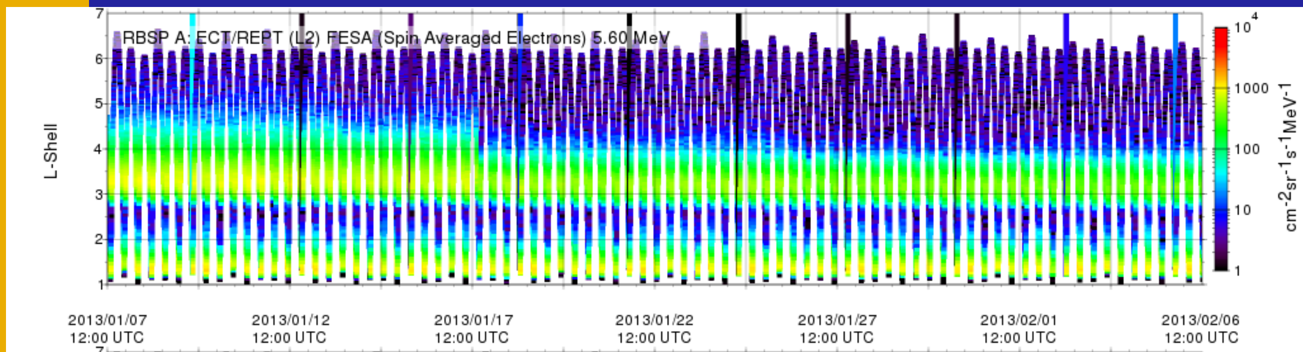
EMIC wave event on 18-19 January 2013

Event from: Clilverd et al. (2017), *J. Geophys. Res.*, 122, doi:10.1002/2016JA022812.

Waves seen on GOES from **~22:00 to 01:00 UT** (reported by **Blum et al. [JGR, 2015]**).



Evidence of approx. MeV precipitation from AARDDVARK, BARREL, and Halley riometer



RBSP 5.6 MeV trapped electron fluxes

Clearly a notch in the ultrarelativistic fluxes from **~17:35UT** on 17 January 2013, down to about *L*=4.0.

decrease seen about a day before this wave event. **close enough in time?**

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What do those case studies mean?

I selected some EMIC wave events and looked at the RBSP events. HOWEVER, most were not random, as they were selected because I had other evidence very near these times that precipitation was taking place.

A few examples I have not show did not have an ultra-relativistic dropout, but most did. For the events I considered there was evidence of:

1. an EMIC wave event observed,

2. precipitation of electrons (but hundreds of keV to a MeV),

3. a dropout in relativistic fluxes occurring closeish in time, sometimes before the waves, sometimes hours after.

But, a 5.5 MeV at L=4.5 will take ~3.5 minutes to drift around the Earth.

I worry that offsets of hours between the wave time and the dropout time might not indicate that those waves have caused that dropout, but rather a process which leads to the dropout also triggers the waves. In my opinion we need to be more careful about timescales.

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But ANYWAY

- There is a strong suggestion in the literature that EMIC waves may be extremely efficient scatterers of ultra relativistic electrons at *L*-shells like *L*=4.0 and *L*=4.5.
- Large changes in trapped fluxes in these *L*-shells and energy have been reported, linked to the (rough) timing of those waves.
- Theory has been put forward to back this up.
- <u>However,</u> at this time, no precipitation observations have been reported for such energies (but then I do not think there are appropriate sensors which would discriminate those energies).

At the same time, there is a growing body of studies, both space and ground based, indicating EMIC waves can provide efficient scattering of hundred's of keV electrons.

Can both of these things be true?

Satellite Observations of EEP from POES

Orbit: ~835 km Sun synchronous.

While suffering from numerous limitations, POES is the most widely used source of space based EEP observations (and includes the BLC) with really long datasets available!

POES SEM-2 MEPED starts in 1998 and data is still being produced!

Satellite	Orbital Sector	Data Availability	
NOAA 15	Morning	1st July 1998	Still Active
NOAA 16	Afternoon	10th January 2001	Dead Since June 2014
NOAA 17	Morning	12th July 2002	Dead Since April 2013
NOAA 18	Afternoon	7th June 2005	Still Active
METOP 02	Morning	3rd December 2006	Still Active
NOAA 19	Afternoon	23rd February 2009	Still Active
METOP 01	Morning	1 January 2013	Still Active

POES precipitation events with a certain signature have been linked to EMIC wave observations (i.e., EMIC wave scattering), leading to 3777 events from 1998-2015.

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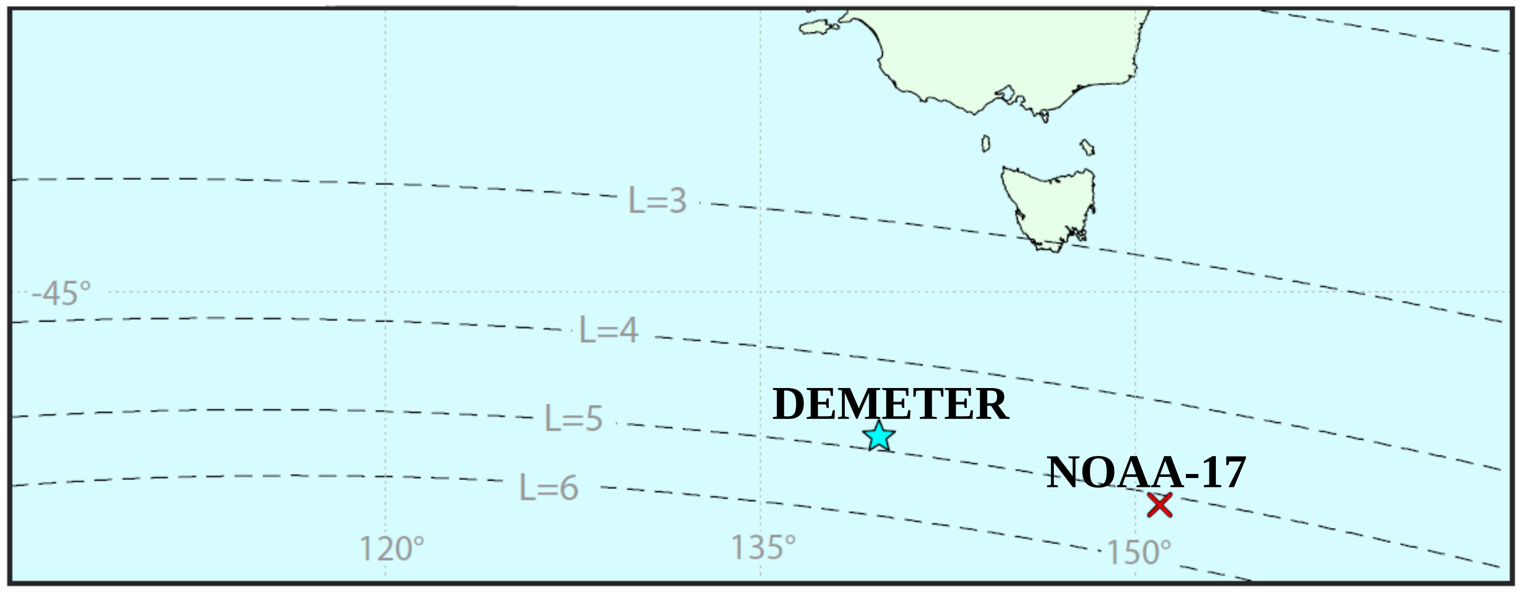
Case study sanity check – use the IDP on the DEMETER spacecraft.

- First of the Myriade series of microsatellites developed by the Centre National d'Études Spatiales (France).
- Instrument include:
  ICE (Electric field)
  IDP (Energetic particles)
- Data for invariant latitudes below ~65°, ie., *L*~1-7
- Low Earth orbit: 710km altitude
- Sun-synchronous polar orbit at 10:30 and 22:30 LT.
- Operation June 2004 – March 2011.

http://smsc.cnes.fr/DEMETER/index.htm

Case Study Example: 18 November 2005



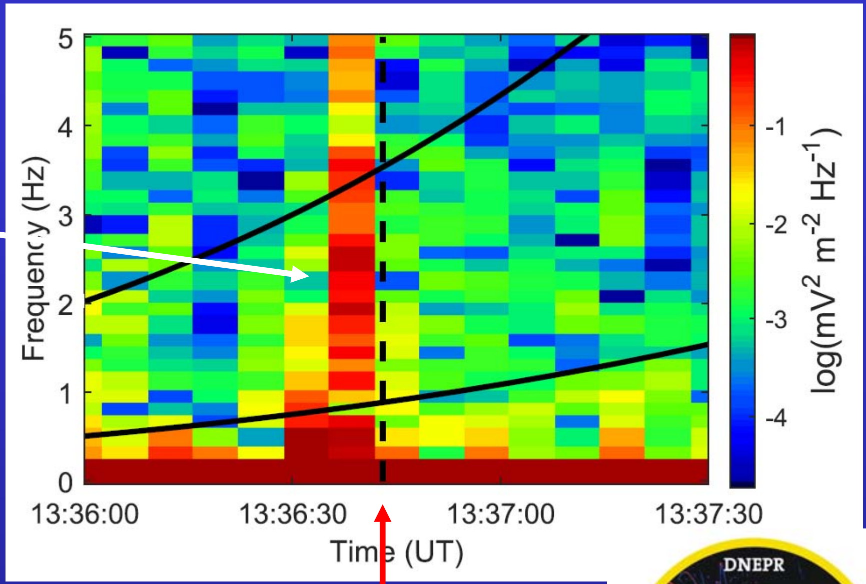
POES trigger at 13:00:31 UT
(satellite located at L = 5.1 and 0.6 MLT)

Nearby DEMETER pass at 13:36:43 UT
(satellite located at L = 5.2 and 23.9 MLT)

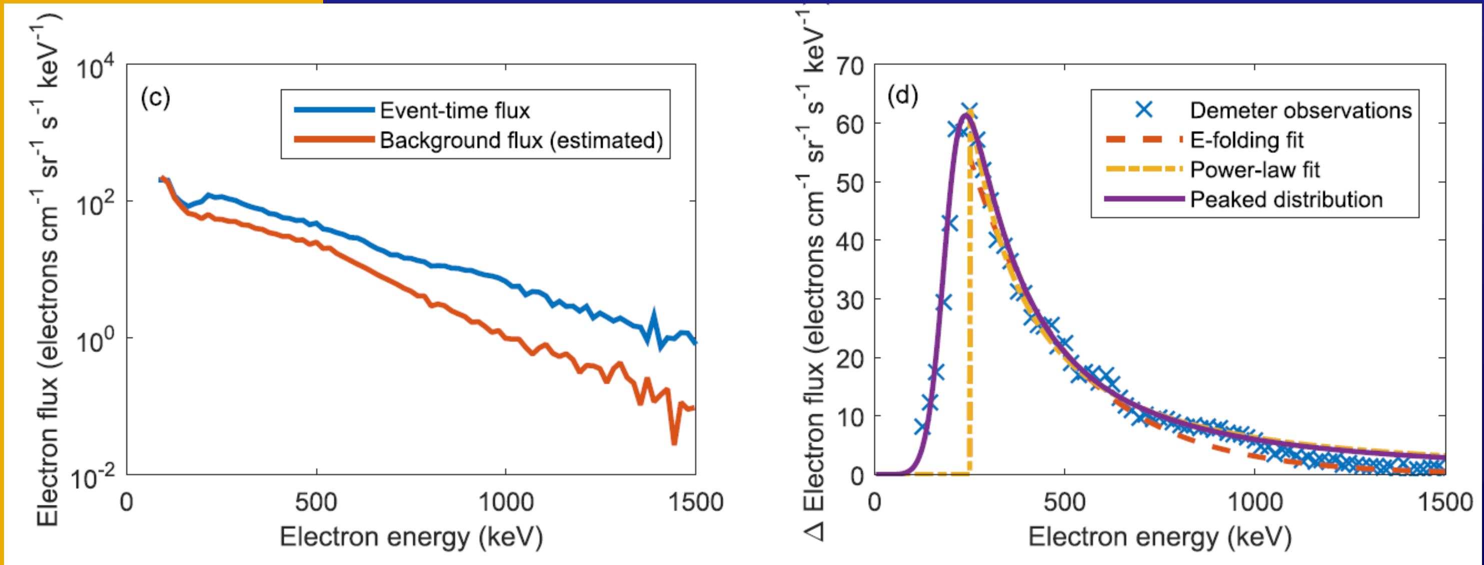
$\Delta T \approx$ 37 min, ΔL=0.1, ΔMLT=0.7

Case Study Example: 18 November 2005

DEMETER/ICE shows evidence of possible EMIC wave activity, with an increase in wave power between the H- and He- gyrofrequencies.



Time of DEMETER/IDP electron flux increase



DEMETER/IDP electron flux change. Note how the fluxes are well fit by a "peaked distribution".

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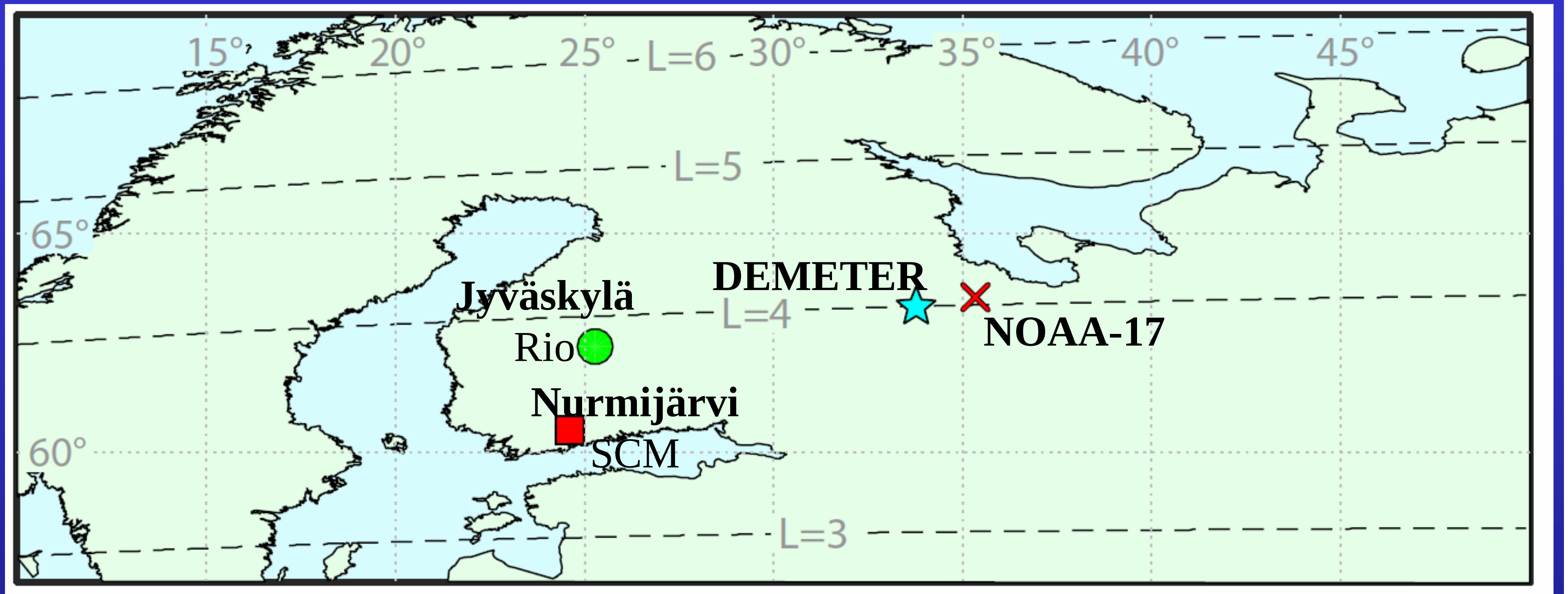
Case Study Example: 4 June 2005



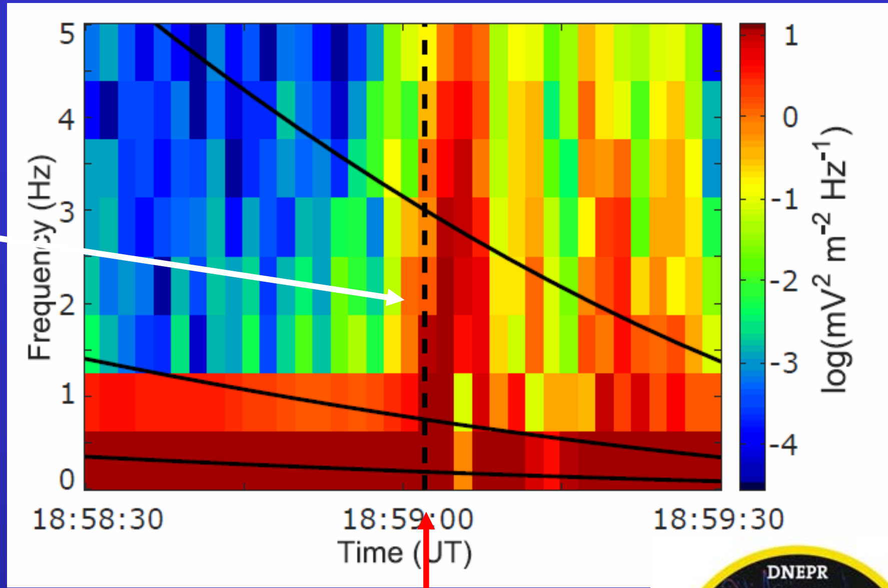
POES trigger at 18:59:24 UT
(satellite located at L = 4.0 and 22.6 MLT)

Nearby DEMETER pass at 18:59:02 UT
(satellite located at L = 4.0 and 22.5 MLT)

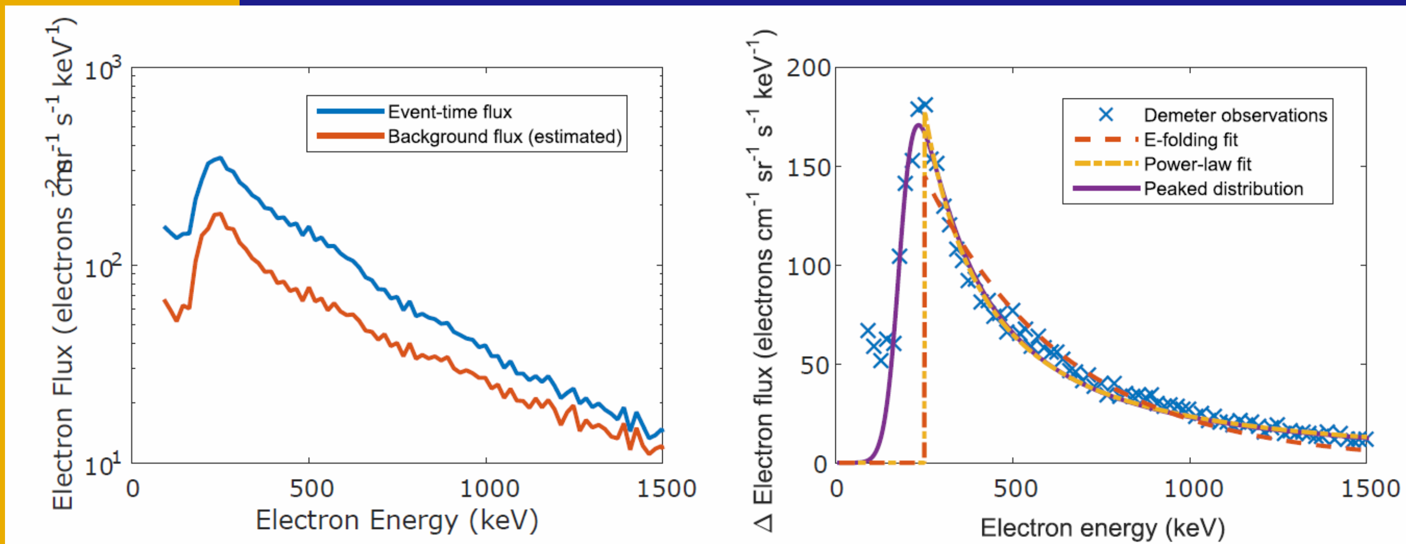
$\Delta T \approx$ 22 secs, ΔL=0.0, ΔMLT=0.1

Case Study Example: 18 November 2005

DEMETER/ICE shows evidence of possible EMIC wave activity, with an increase in wave power which might be between the H- and He-gyrofrequencies.



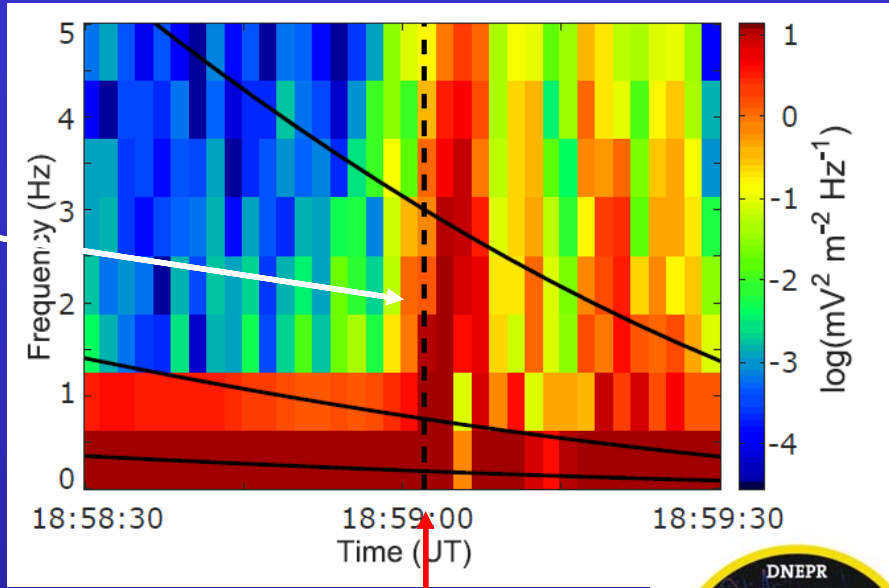
Time of DEMETER/IDP electron flux increase



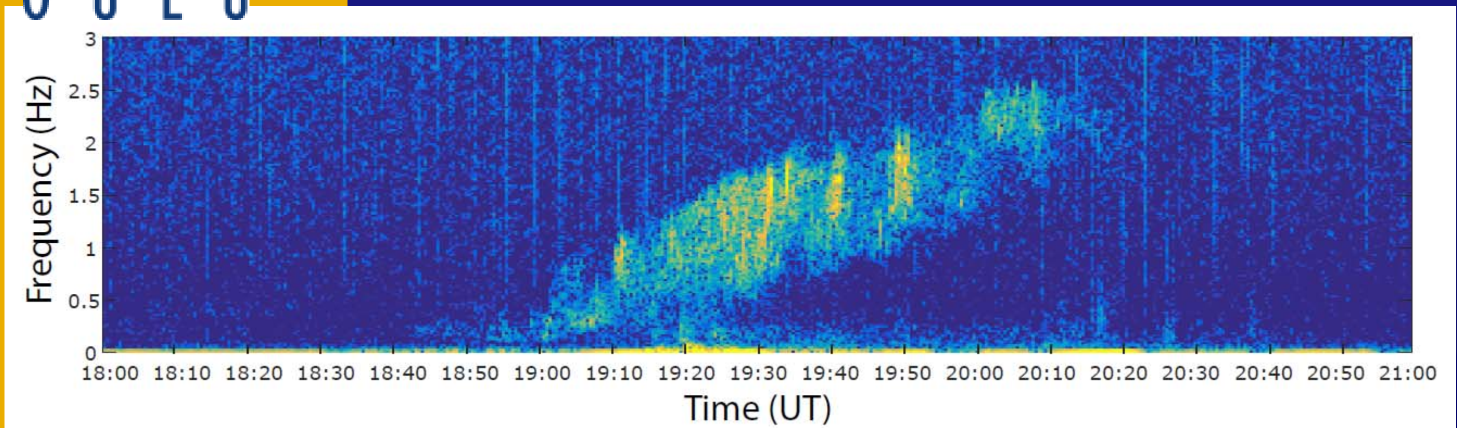
DEMETER/IDP electron flux change. Note how the fluxes are well fit by a peaked distribution.

Case Study Example: 18 November 2005

DEMETER/ICE shows evidence of possible EMIC wave activity, with an increase in wave power which might be between the H- and He-gyrofrequencies.



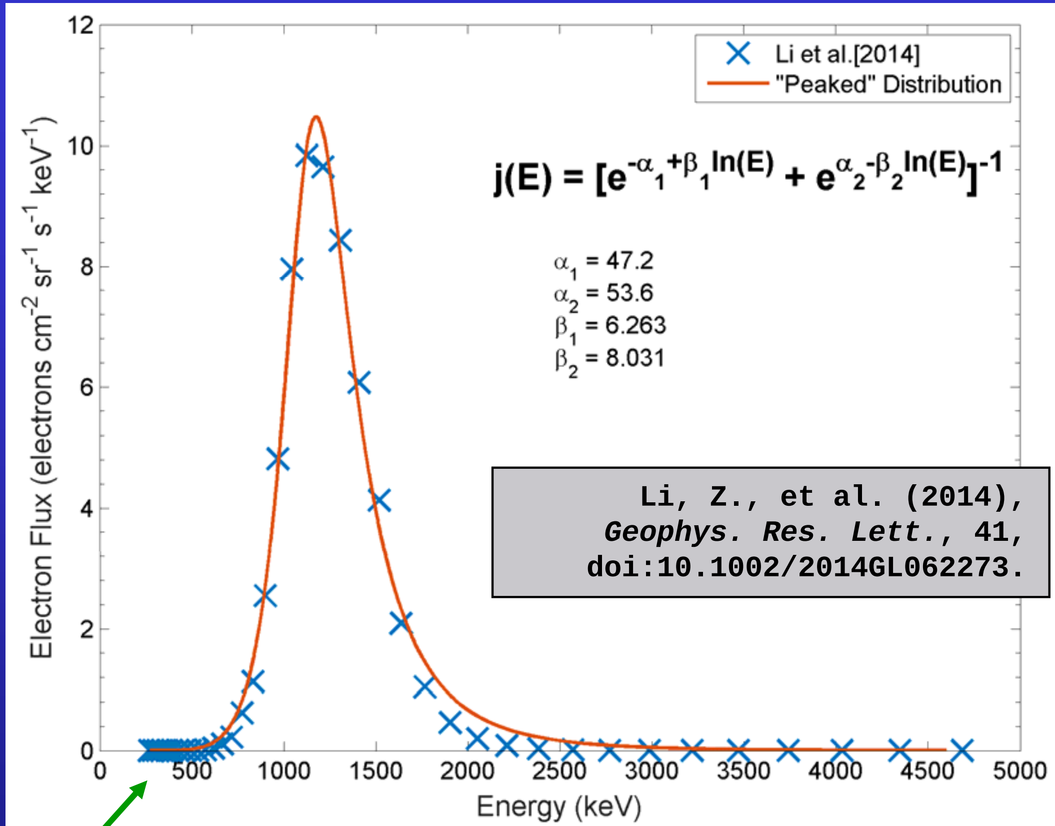
Time of DEMETER/IDP electron flux increase



But on the ground there is a definite IPDP EMIC wave seen at Nurmijärvi from ~19:00 to ~20:10 UT

Peaked Distributions

In DEMETER data these events look a bit like a gradual rise followed by a fall off of flux with energy. From this we make a "peaked" flux distribution defined by a energy (*Ep*) where the peak lies.



In the DEMETER data we are seeing a rather similar shape to that predicted by *Li et al.* [2014] for EMIC driven precipitation (using RBSP and GOES-13 input parameters, which did a good job of reproducing BARREL X-ray counts).

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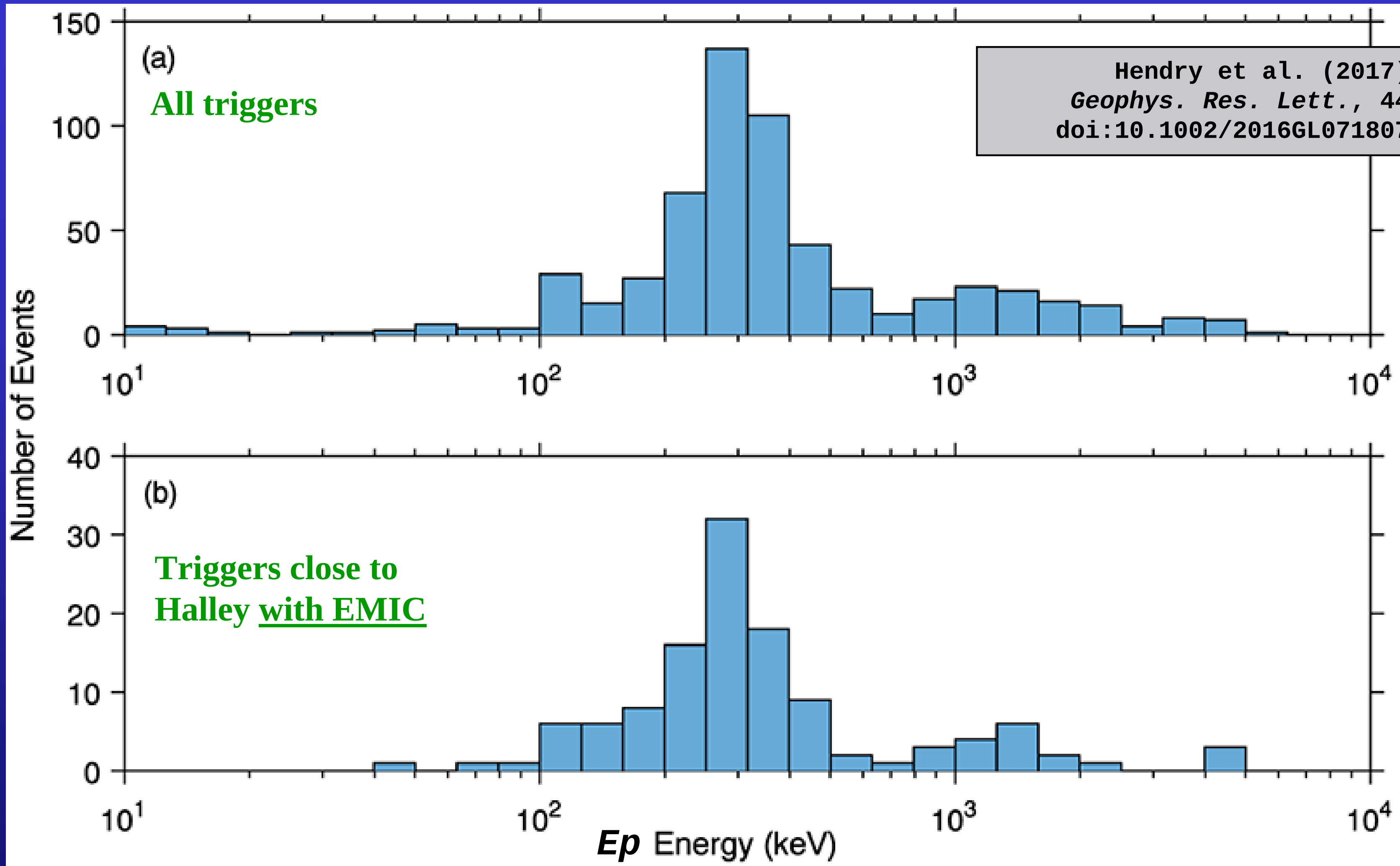
Peaked Distributions – POES trigger fits



Hendry et al. (2017), *Geophys. Res. Lett.*, 44, doi:10.1002/2016GL071807.

All POES triggers (with good fits, 610 events)

- Dominant population (~53%) have *Ep* values around 200–500 keV
- Secondary maximum (~17%) occurring in the 0.8–4 MeV range.

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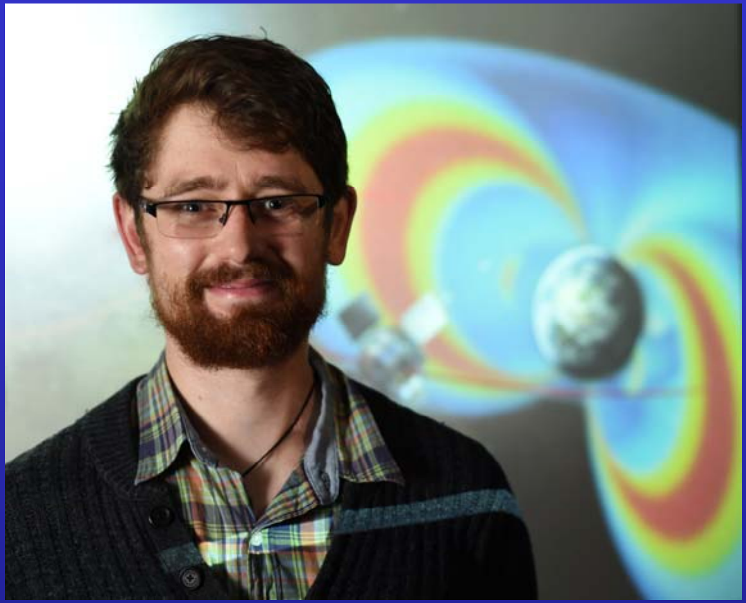
What would this population do to the trapped fluxes at L=4.7?



Aaron made a representative selection of EEP flux fits, based on the properties of the POES triggers (which he has previously shown are associated in time and space with EMIC events).

We then used AE-9 to work out what the differential electron population in a AE-9 flux tube would be, and "hit it" with 10min worth of this precipitation flux.

I used AE9 V1.50.001

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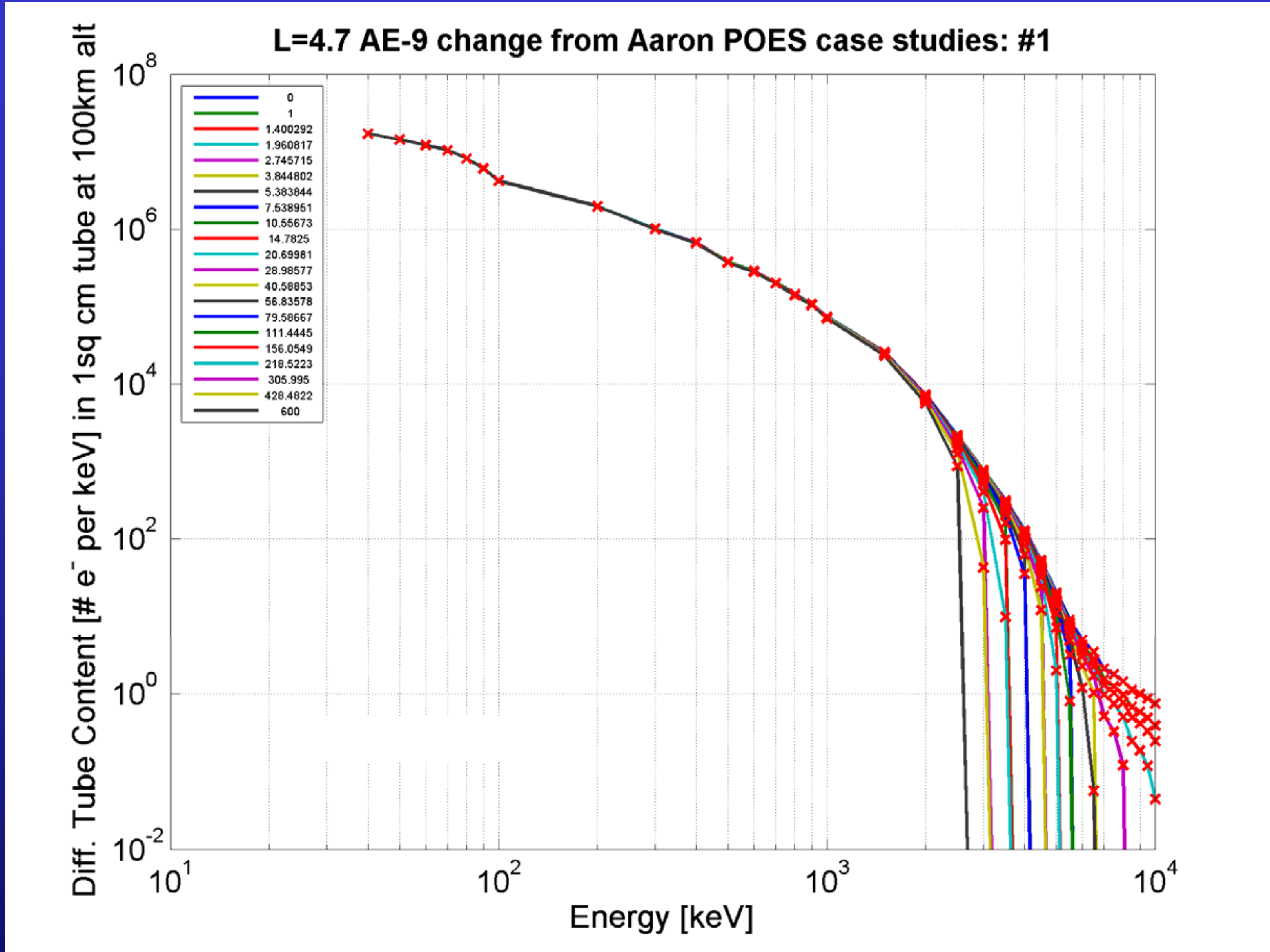
Example 1



>3 MeV fluxes gone in ~10min, <1 MeV no significant change

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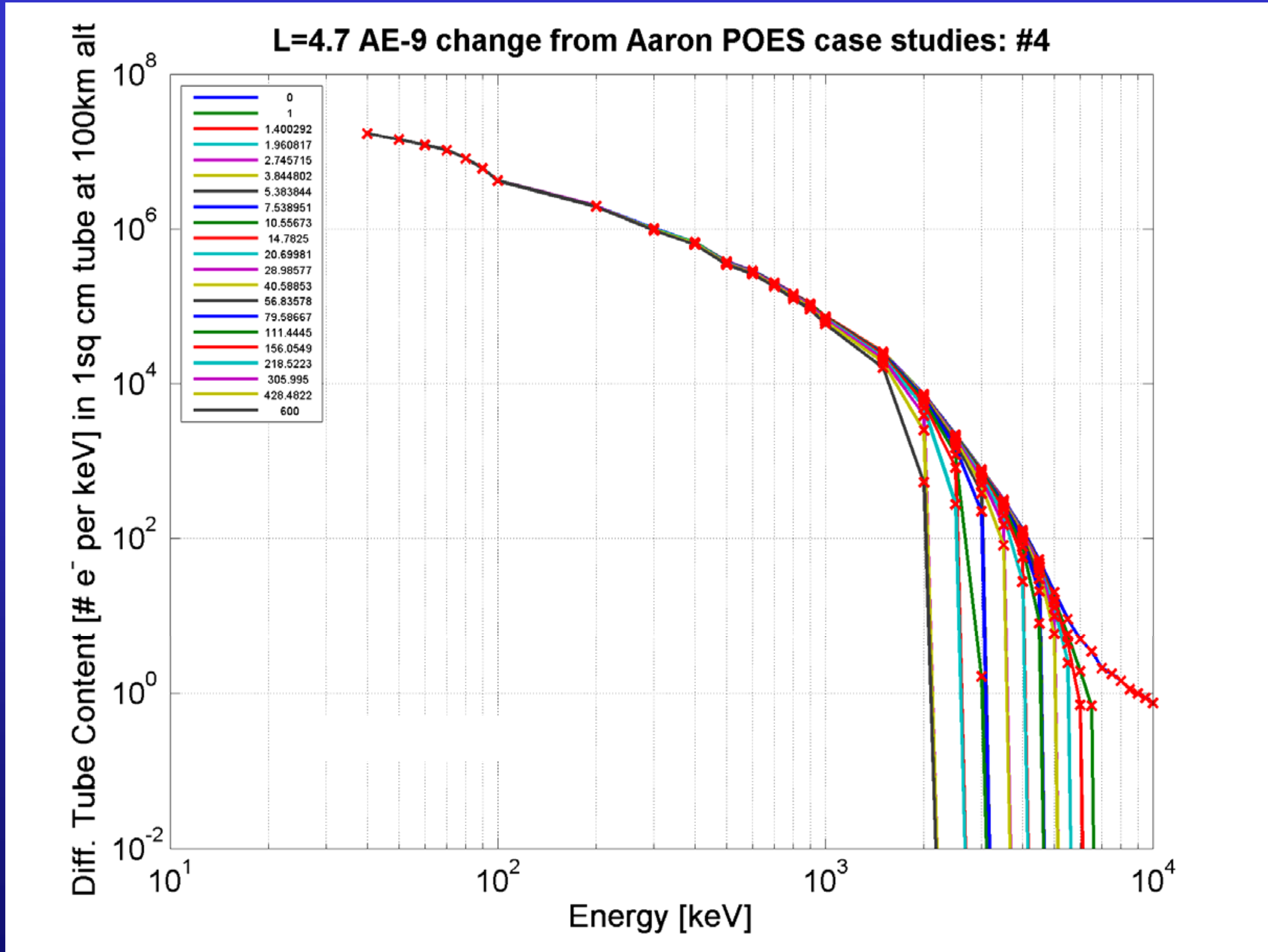
Example 2



>2 MeV fluxes gone in ~10min, <1 MeV no significant change

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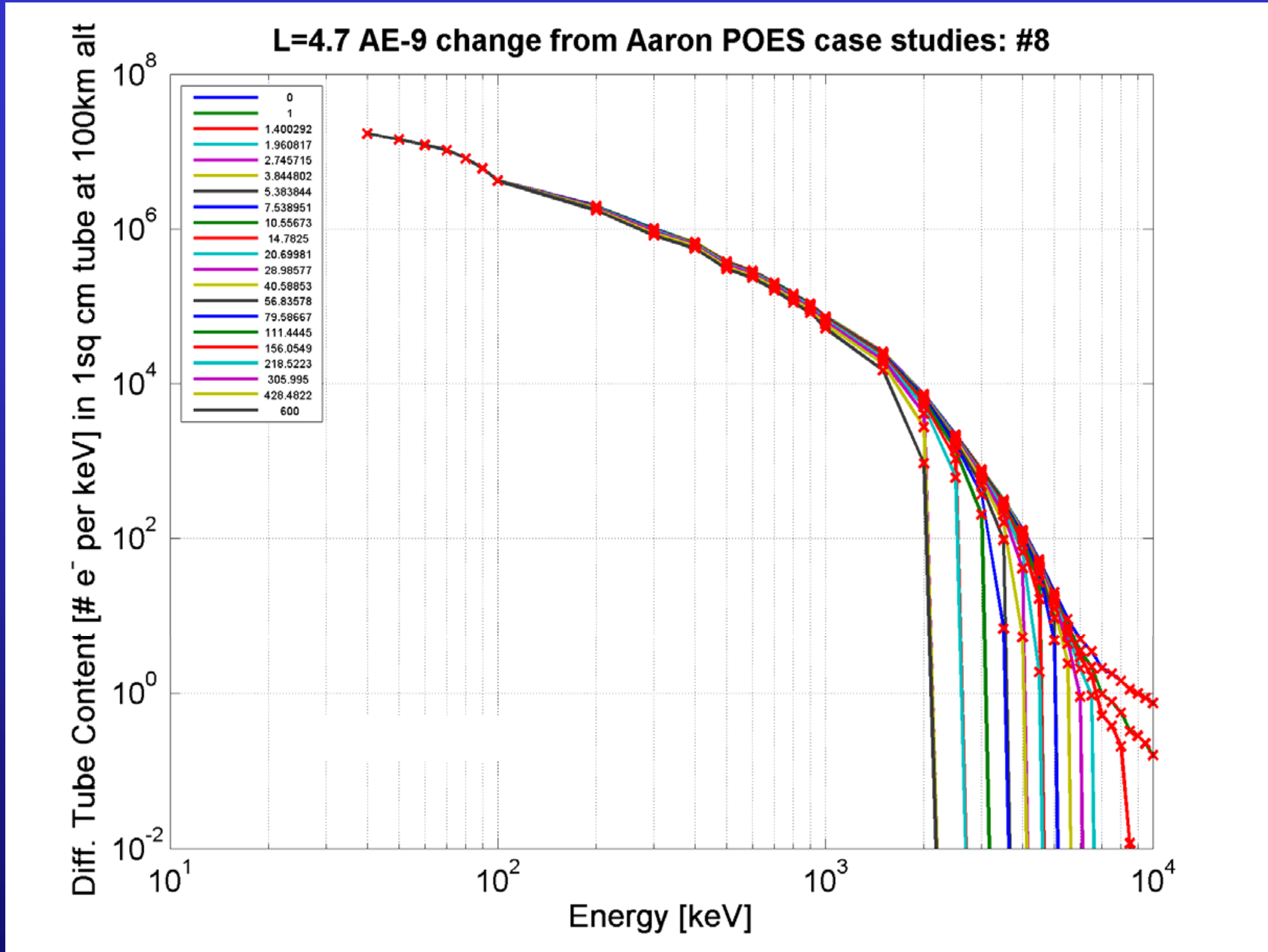
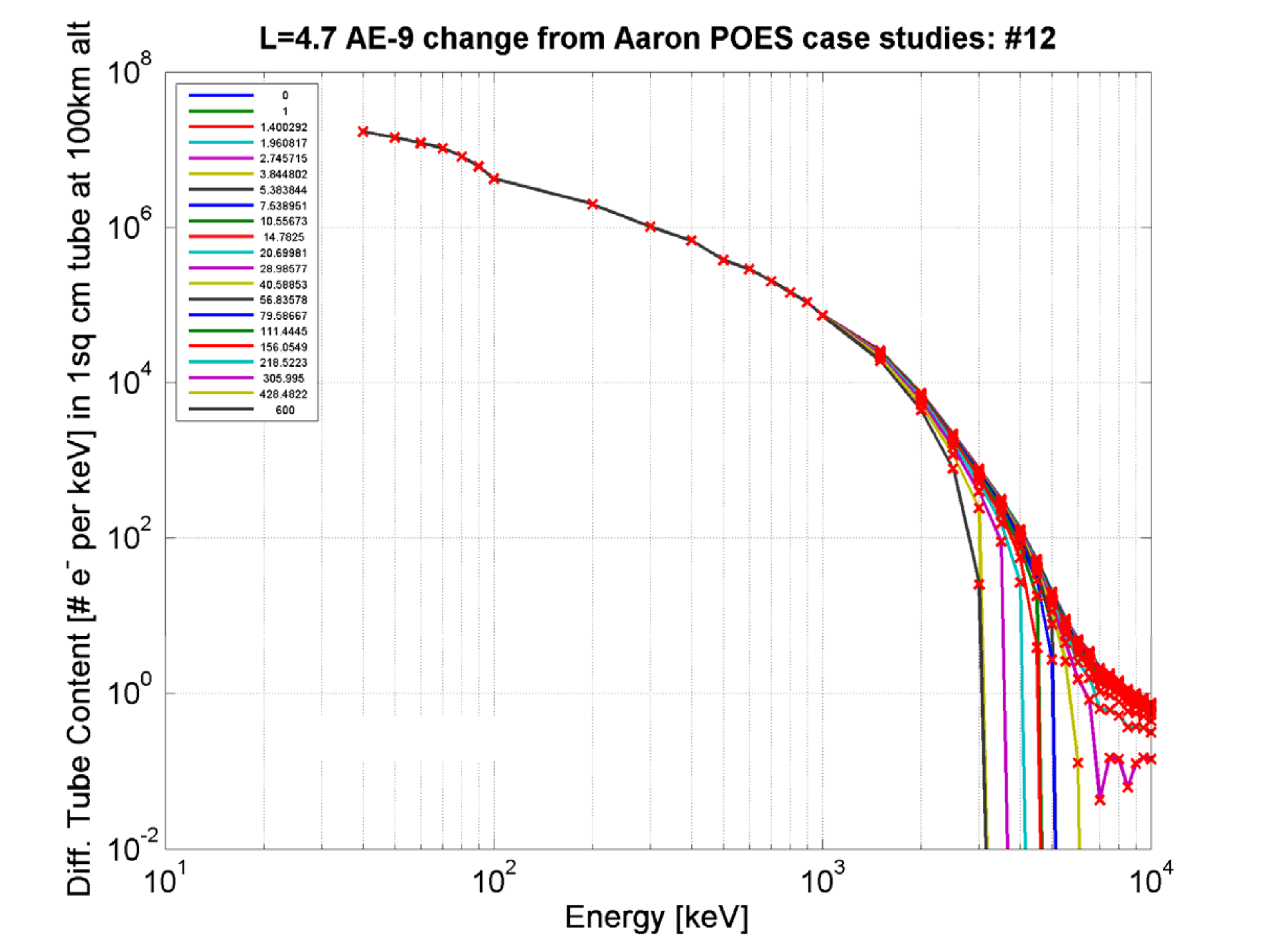
Example 3



>2 MeV fluxes <u>gone</u> in ~10min, <1 MeV tiny change

Example 4



>3 MeV fluxes gone in ~10min, <1 MeV no significant change

Summary

- Currently EMIC is thought to be an important driver for losses of relativistic electrons from the radiation belts.
- EMIC wave events often occurr close in time to RBSP-observed ultra-relativistic electron dropouts down to about L=4.
- The wave observations could be many hours before the dropout, which is troubling for an electron going around the world in <5min.
- There are no experimental reports (yet) of ultra-relativistic precipitation observed for these events (that I know of).
- There are experimental reports of EMIC-linked precipitation events which peak at a few hundred keV, but with a tail out to MeV.
- It is possible for those EMIC events to produce a relativistic dropout and no significant change in the ~300keV trapped fluxes.

Craig Rodger gives a talk on Space Weather at "The Sunroom", a public art installation [20 June 2017].

Thankyou!

Is there time for questions?

EMIC Wave-produced precipitation

As strange as this might seem, for a theoretical concept that goes back decades, experimental evidence for scattering and precipitation of energetic and relativistic electrons are quite rare in the literature!

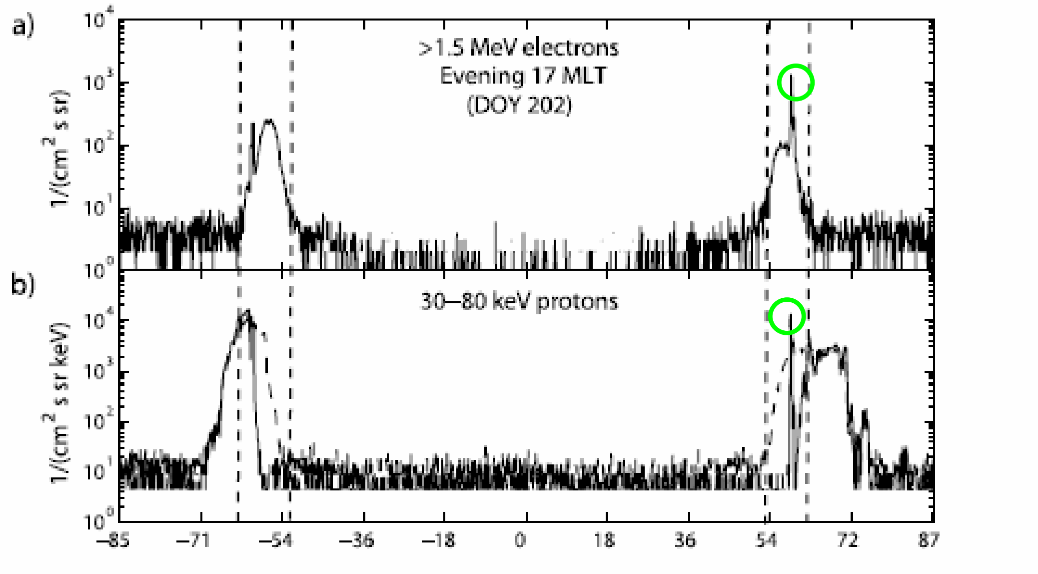


Figure 4. Particle data from NOAA-12 on 21 and 26 July 1998. The figure exhibits electrons >1.5 MeV and protons 30–80 keV, from the 90deg (dashed line) and 0deg detectors (a and b) from an eveningside pole-to-pole orbit on 21 July (1215–1305 UT) and (c and d) from an eveningside pole-to-pole orbit on 26 July (0700–0751 UT).

Example of suspected EMIC-scattering signature reported previously by *Sandanger et al.* [2007] (in this case from NOAA-12 data, i.e., an SEM-1 carrying satellite). Similar examples were reported by *Sandanger et al.* [2009].

Sandanger et al. (2007), *J. Geophys. Res.*, 112, doi:10.1029/2006JA012138.

Marit Sandanger reported simultaneous spikes seen in NOAA POES in the precipitating protons (ten's of keV) and also in the relativistic electron flux, which they claimed were probably caused by EMIC.

[My students have subsequently built up a database of thousands of these events following on from her examples]

Fluxes but no waves

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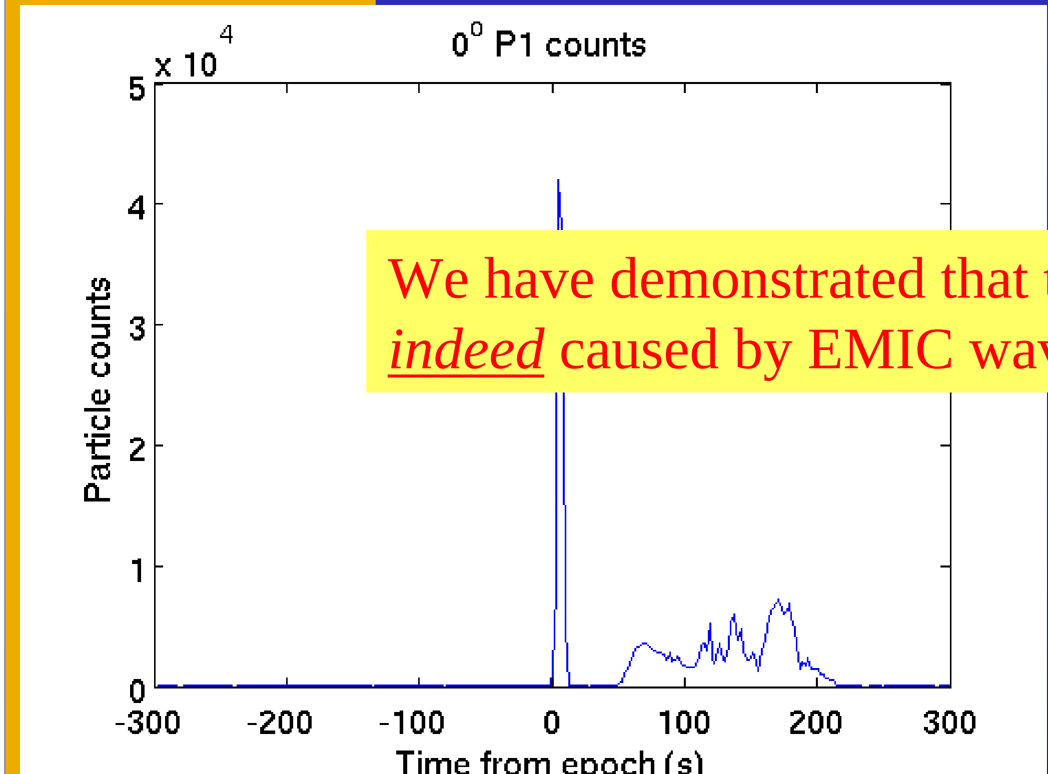
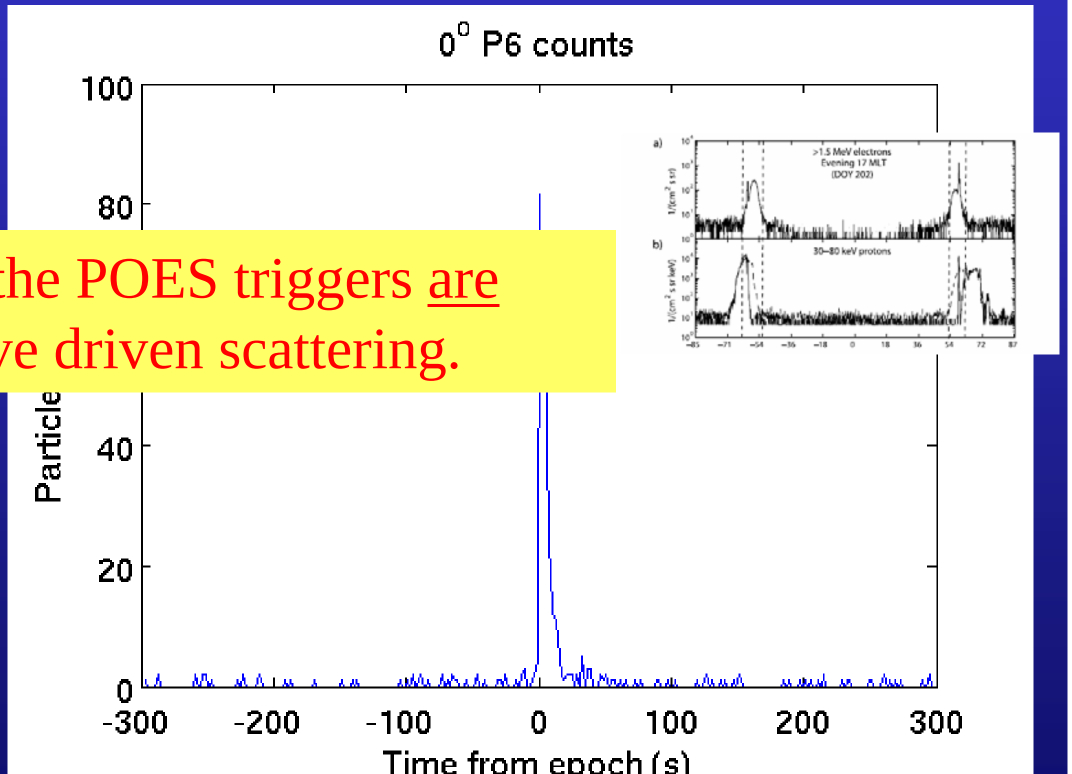
Searching for EMIC precipitation with POES

One of my MSc Students, Bonar Carson, made an EMIC precipitation detection algorithm to find the "spike" events seen in the *Sandanger et al.* [2007] and *Sandanger et al.* [2009] studies.

He scanned through 1998-2010 POES SEM-2 data and found **2331 triggers**



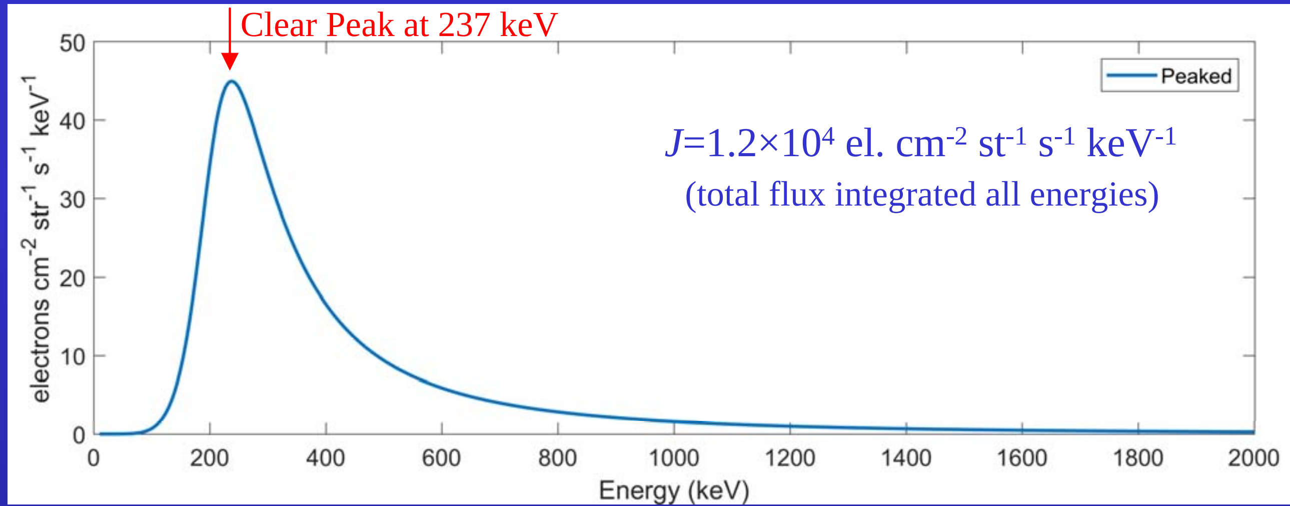


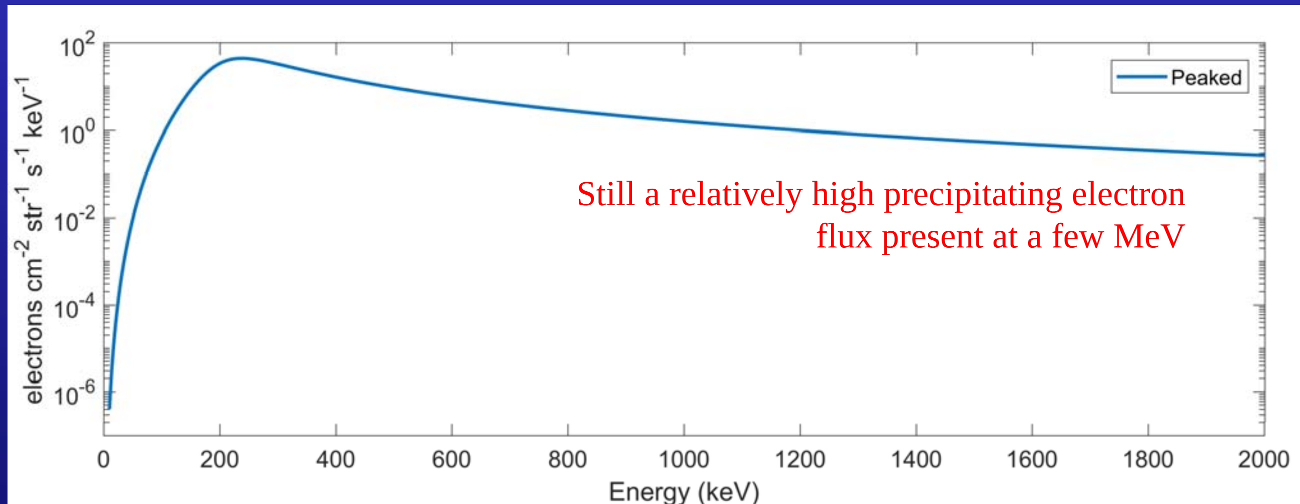
We have demonstrated that the POES triggers ***are indeed*** caused by EMIC wave driven scattering.

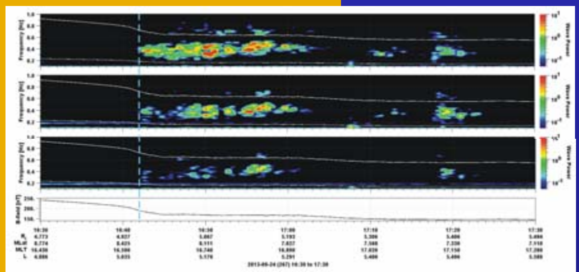
Algorithm described in: Carson et al., J. Geophys. Res., 118, 1-12, doi:10.1029/2012JA017998, 2013

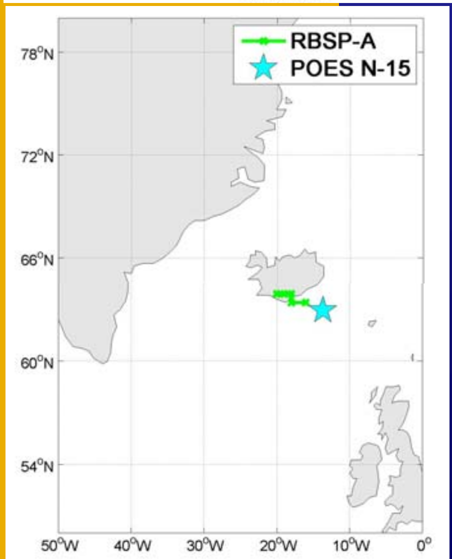
Otago PhD student Aaron Hendry has used the algorithm on an extended dataset through to 2015 (plus included MetOp-01 data) and found **3,777 triggers**.

Peaked Distributions - RBSP event









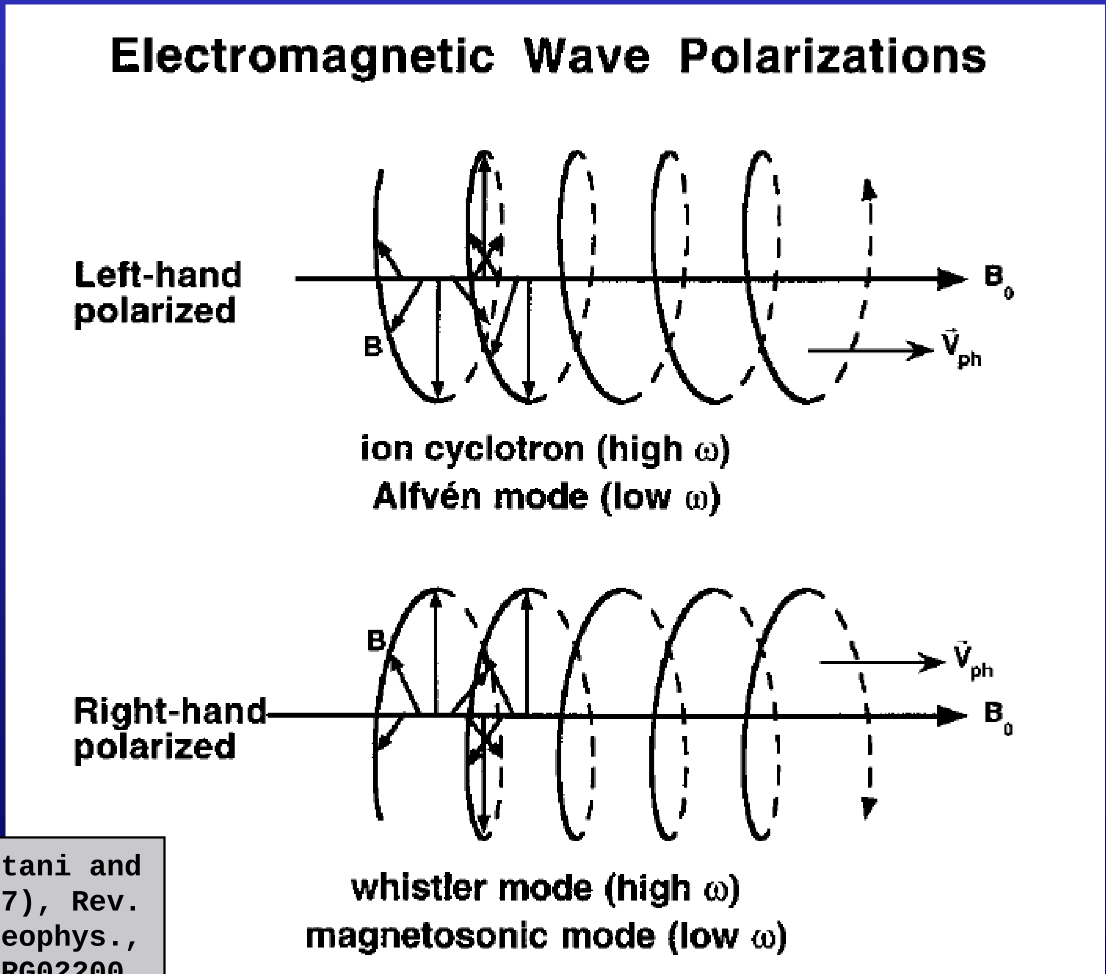
We fitted a "peaked" distribution to the POES proton and electron fluxes. Has a lower energy component than expected from "basic" cyclotron theory, but it also has a very strong relativistic component.

EMIC Waves = ion cyclotron waves

Charged particles in the geomagnetic field gyrate (from basic physics).

It turns out that the standard propagation modes for electromagnetic waves in plasma are (approximately) circularly polarised, with EMIC waves being LH polarised. **These waves are said to be in the ion cyclotron mode.**

EMIC = ElectroMagnetic Ion Cyclotron



Plot from Tsurutani and Lakhina (1997), Rev. Geophys., doi:10.1029/97RG02200.

EMIC/ion cyclotron mode

Examples: IPDP, bands, bursts, emissions.

Contrast with the whistler mode

Examples: whistlers, chorus, hiss.

EMIC Waves – precipitation signature

“normal” cyclotron resonance ⇒ proton loss

EMIC waves will regularly pitch angle scatter, and hence precipitate, protons of tens to hundreds of keV energy through first-order cyclotron resonance. These will deposit their energy into the atmosphere at altitudes above ~95 km.

“anomalous” cyclotron resonance ⇒ electron loss

EMIC waves can, under certain conditions pitch angle scatter, and hence precipitate, electrons with hundreds to thousands of keV energy through first-order cyclotron resonance (i.e., ~1 MeV relativistic electrons). These will deposit their energy into the atmosphere at altitudes well below ~70 km.