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FORESAIL

Difference solar wind drivers have distinct solar wind properties and geomagnetic impact characterstistics → expected that they influence the outer radiation belt electron flux in a different manner



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## Losses

- 'magnetopause shadowing' (electron drift paths cross the magnetopause → lost from the belts)
- Wave-particle interactions scatter trapped electrons away from the Earth's magnetic bottle (e.g. gyro and Landau resonances with EMIC, hiss, chorus, bounce resonances)

## Energization

- Local wave-particle interactions (chorus)
- Inward transport by Pc4/Pc5 ULF waves

Of the key relevance in this lecture is how different solar wind structures create favorable conditions for different loss and energization mechanisms to occur



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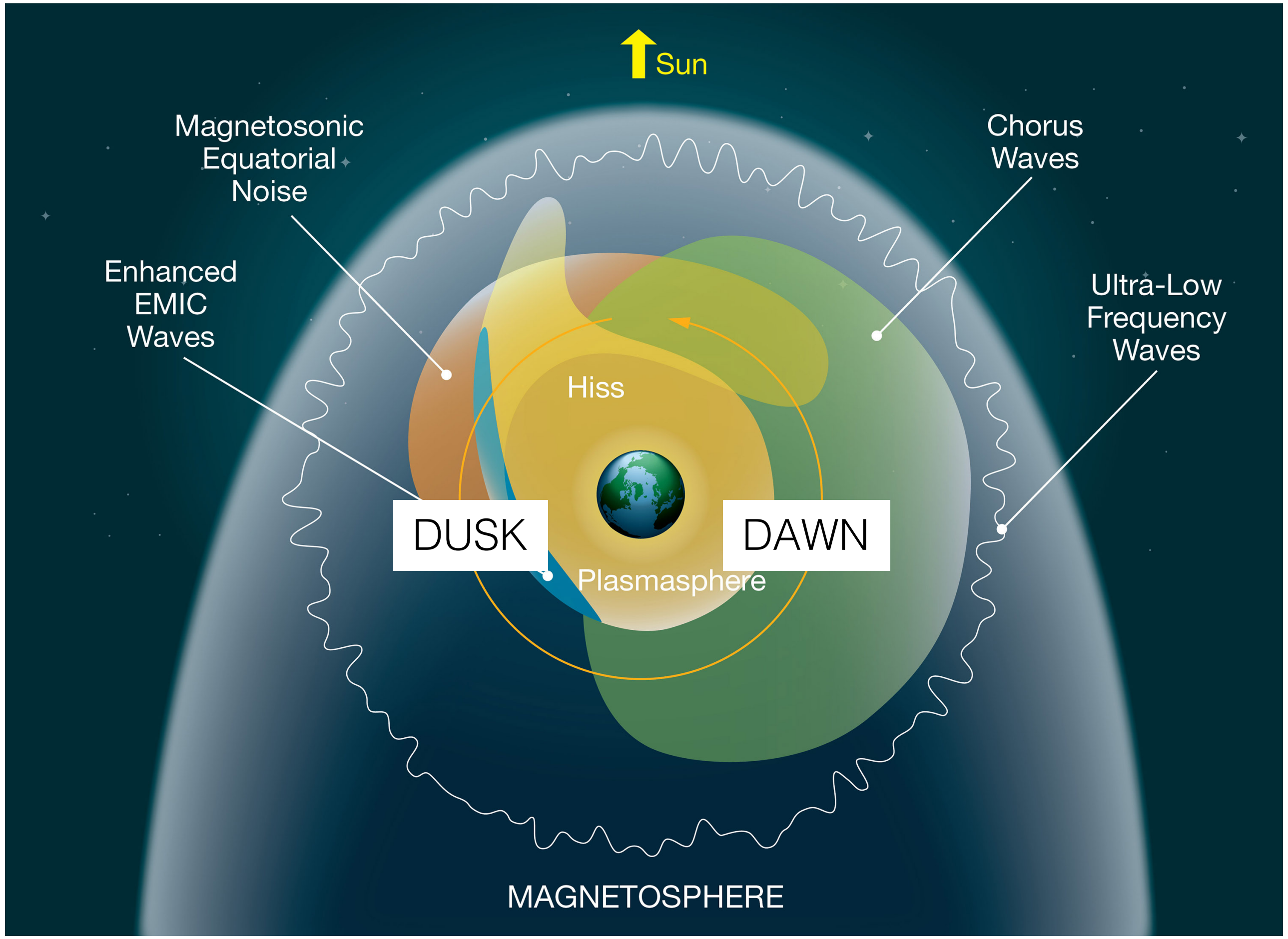


Credits: NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith

Different waves occur at different distances from Earth (whether inside and outside the plasmasphere matters)

Different waves occur at different Magnetic Local Times (MLT) and distances from Earth

Same wave mode can both lead to scattering and enhancement



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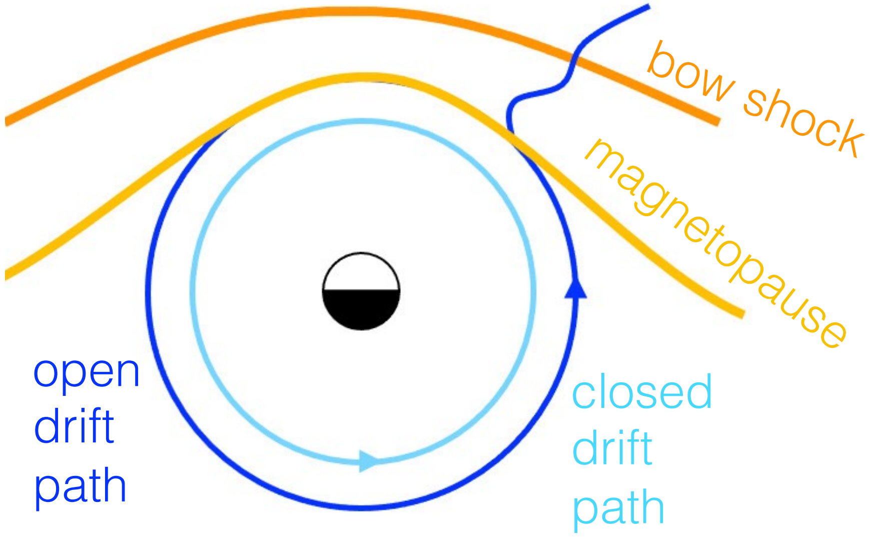
## Magnetopause shadowing losses are affect by the location of the magnetopause and electron’s drift paths




Incursion of the magnetopause inward: This can be caused either by compression due to high dynamic pressure and/or erosion by the dayside magnetic reconnection

Outward radial transport of electrons: This can be caused either by fully adiabatic Dst effect (ring current enhances → Earth’s field weakens → particles move outward) or by outward radial transport by Pc4 – Pc5 ULF waves.



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Radiation belt electrons are divided into different 'populations' based on their energy. They have different origin, perform three adiabatic motions (gyro, bounce, drift) at different times-scales, and interact differently with plasma waves.

(task! find a table from the book and check how long time on average it takes different population to perform different motions)



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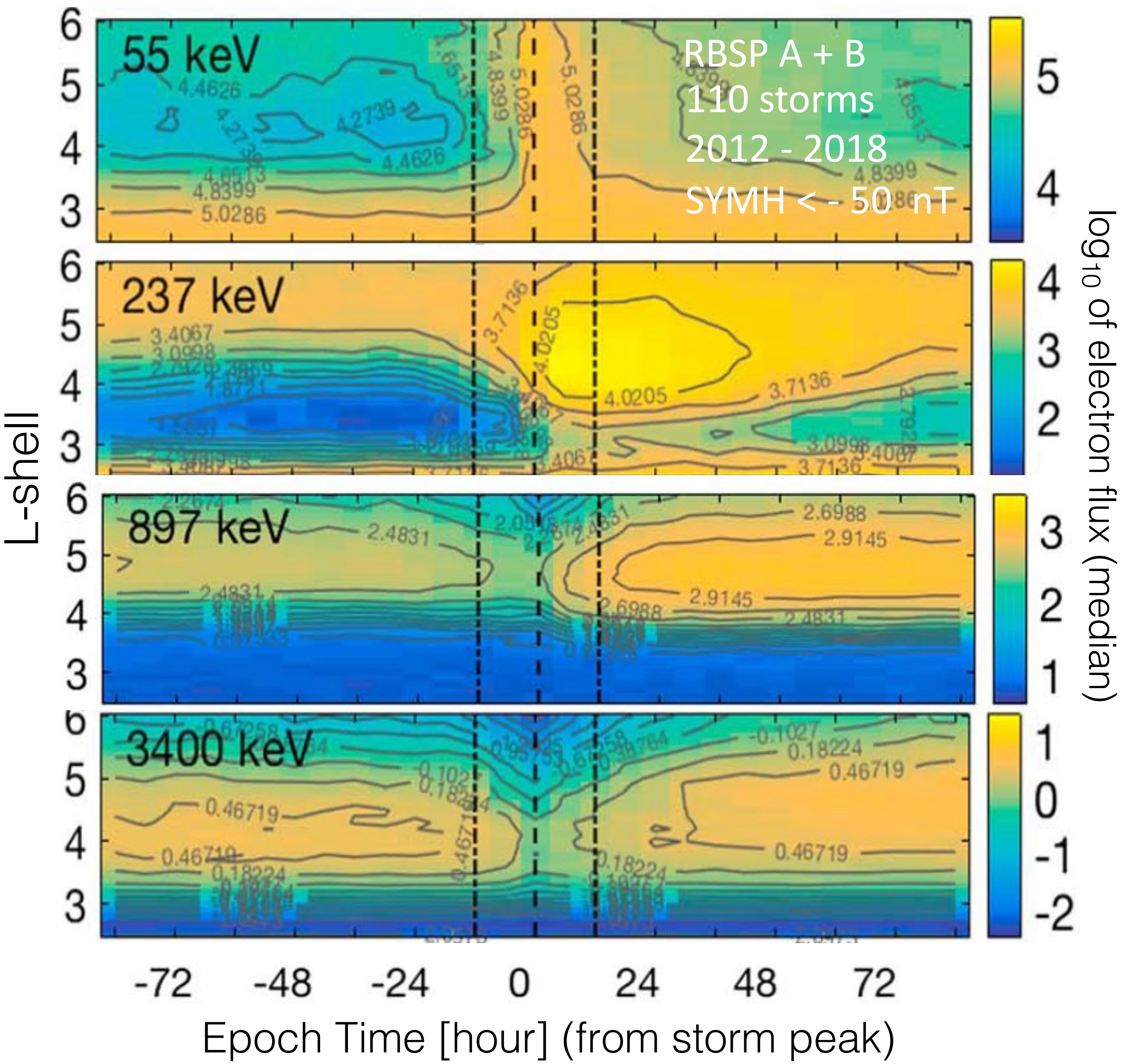


Turner et al., JGR 2019

## Source

- tens of keV
- Substorm injections, convection
- These are 'source' of chorus



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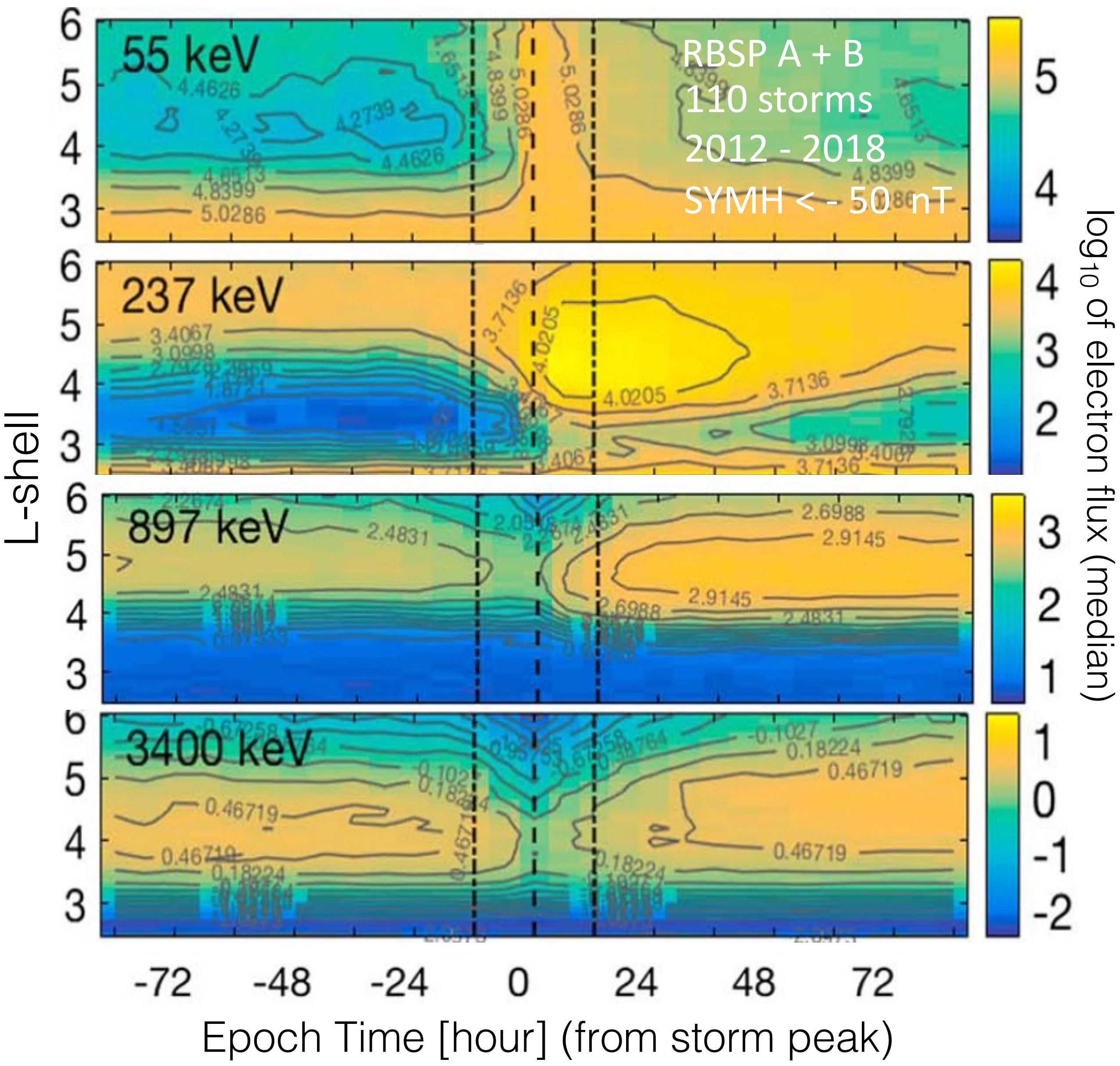


Turner et al., JGR 2019

## Source

- tens of keV
- Substorm injections, convection
- These are ‘source’ of chorus

## Seed

- Few hundred keV
- Substorm injections, convection acceleration by chorus
- These are ‘seed’ of higher enery electrons



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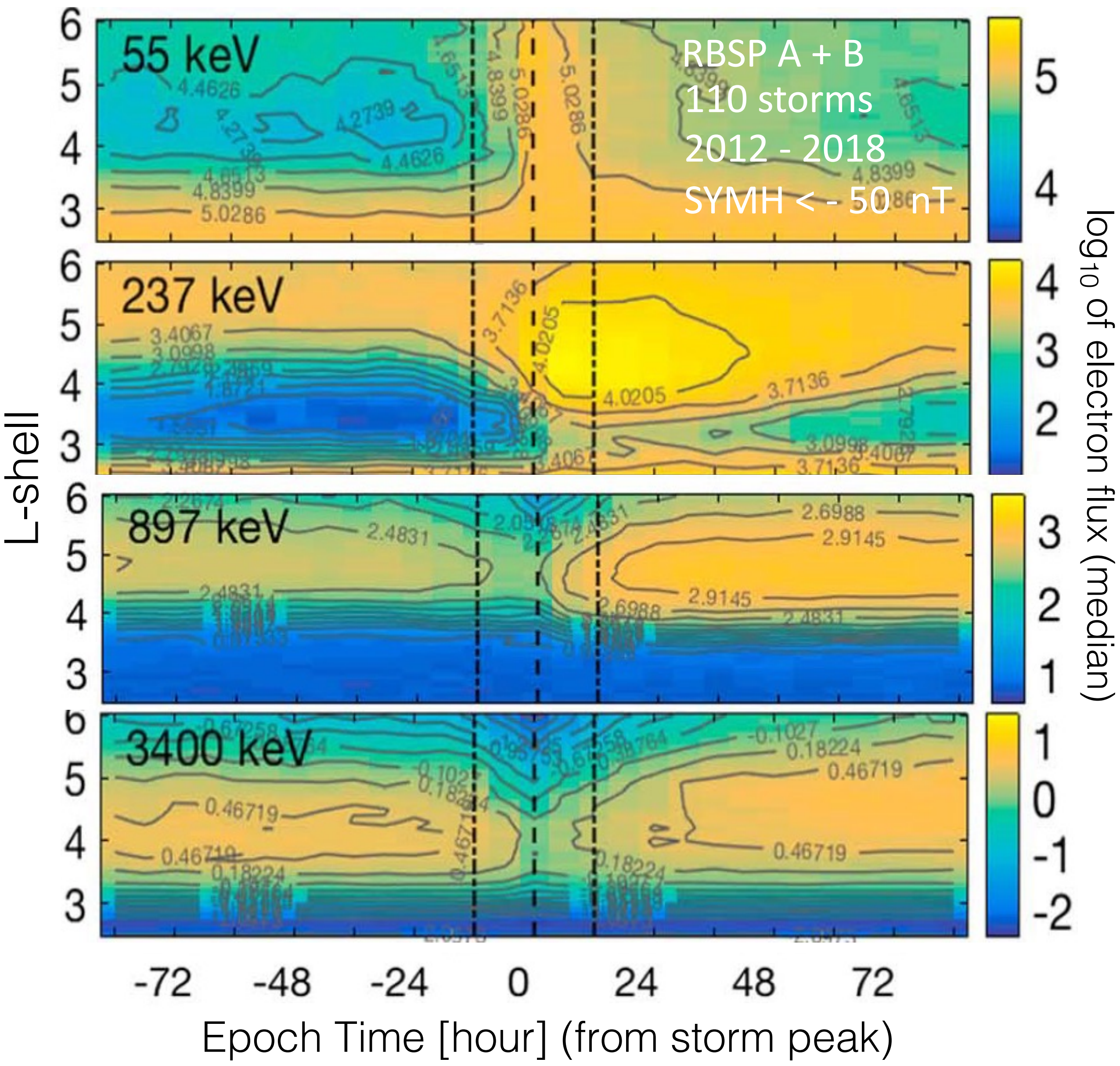


Turner et al., JGR 2019

## Source

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- Few hundred keV
- Substorm injections, convection acceleration by chorus
- These are ‘seed’ of higher enery electrons

## Core (relativistic)

- ~800 keV – 2 MeV
- acceleration by chorus, inward ULF wave transport



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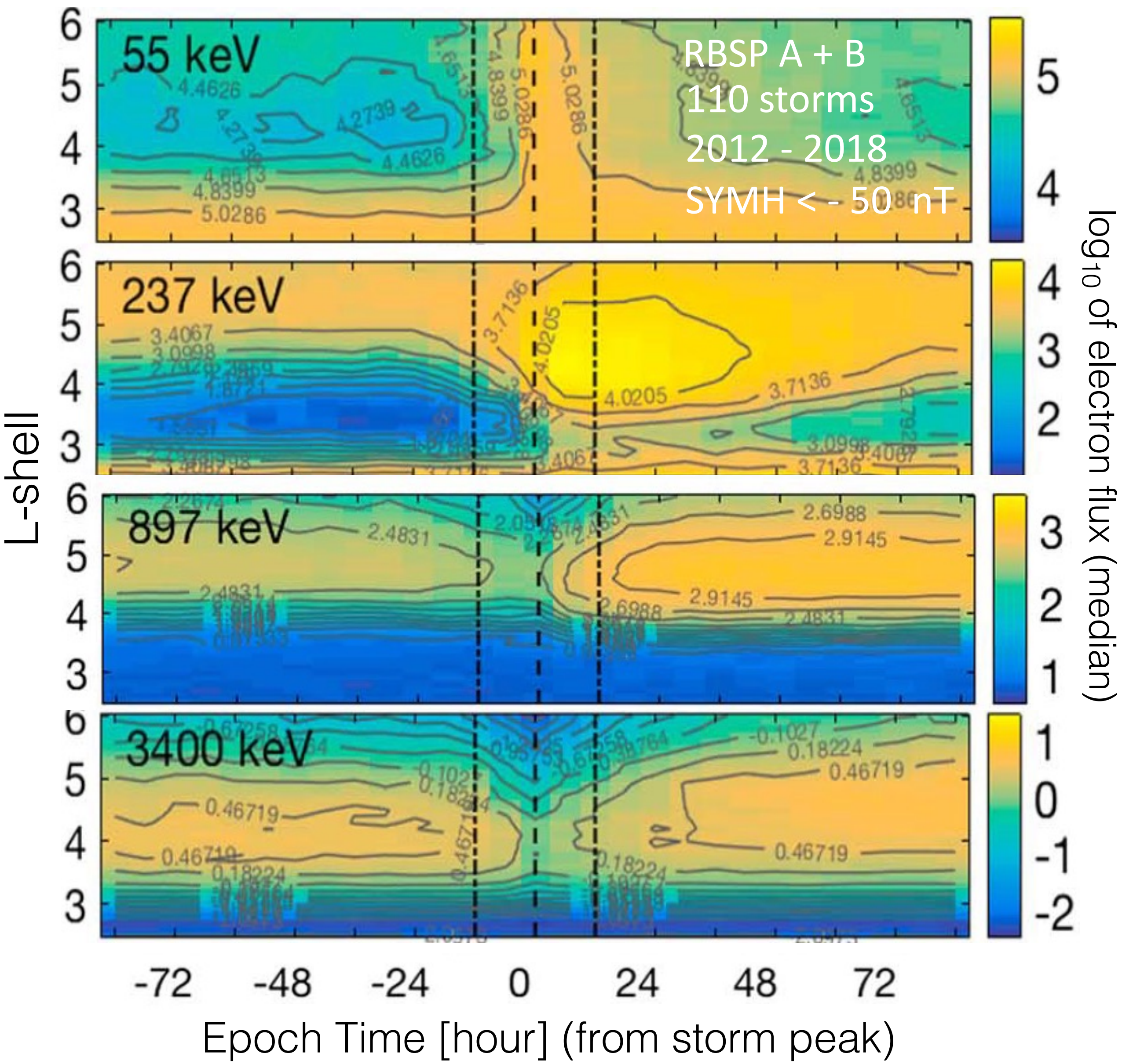


Turner et al., JGR 2019

## Source
- tens of keV
- Substorm injections, convection
- These are 'source' of chorus

## Seed
- Few hundred keV
- Substorm injections, convection acceleration by chorus
- These are 'seed' of higher enery electrons

## Core (relativistic)
- ~800 keV – 2 MeV
- acceleration by chorus, inward ULF wave transport

## Ultra-relativistic ($\gamma > 5$)
- > 2 MeV
- acceleration by chorus, inward transport by ULF waves



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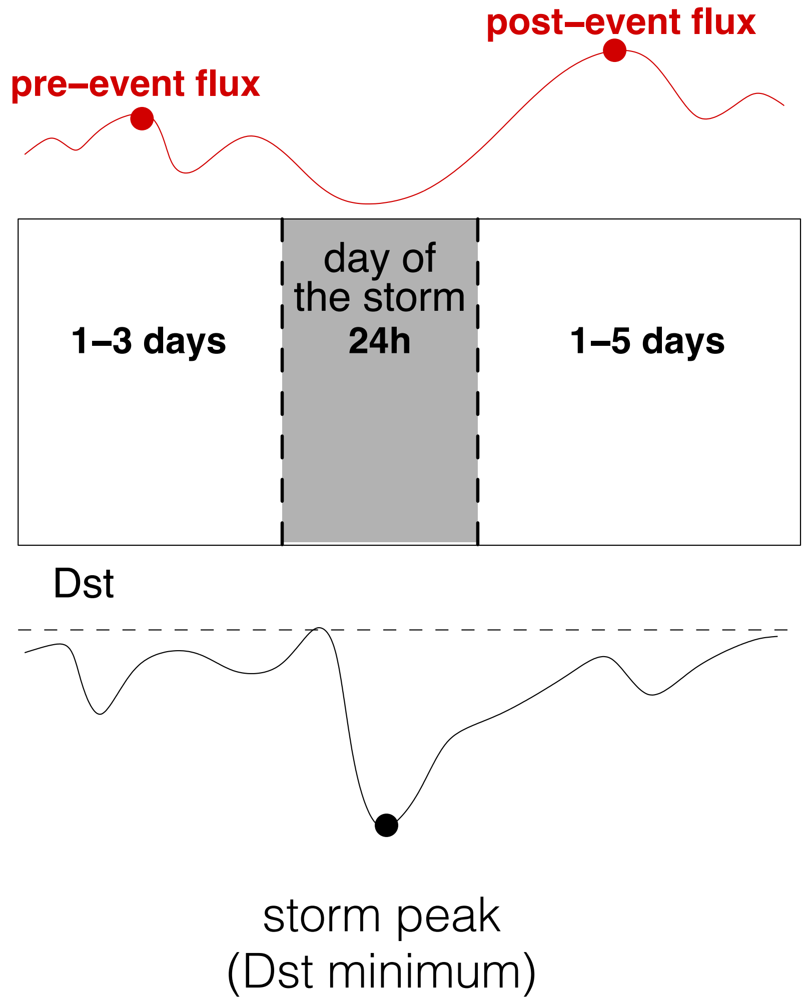


$$R = \frac{\max(\text{pre} - \text{event flux})}{\max(\text{post} - \text{event flux})}$$

$R > 2$: enhancement (53%)

$\frac{1}{2} < R < 2$: no-change (28%)

$R < 2$: depletion (19%)

Reeves et al., 2003 based on 276 storms (1986 – 2000) geostationary > 2 MeV electrons

Why do some storms overall enhance, some deplete and some produce no-change?




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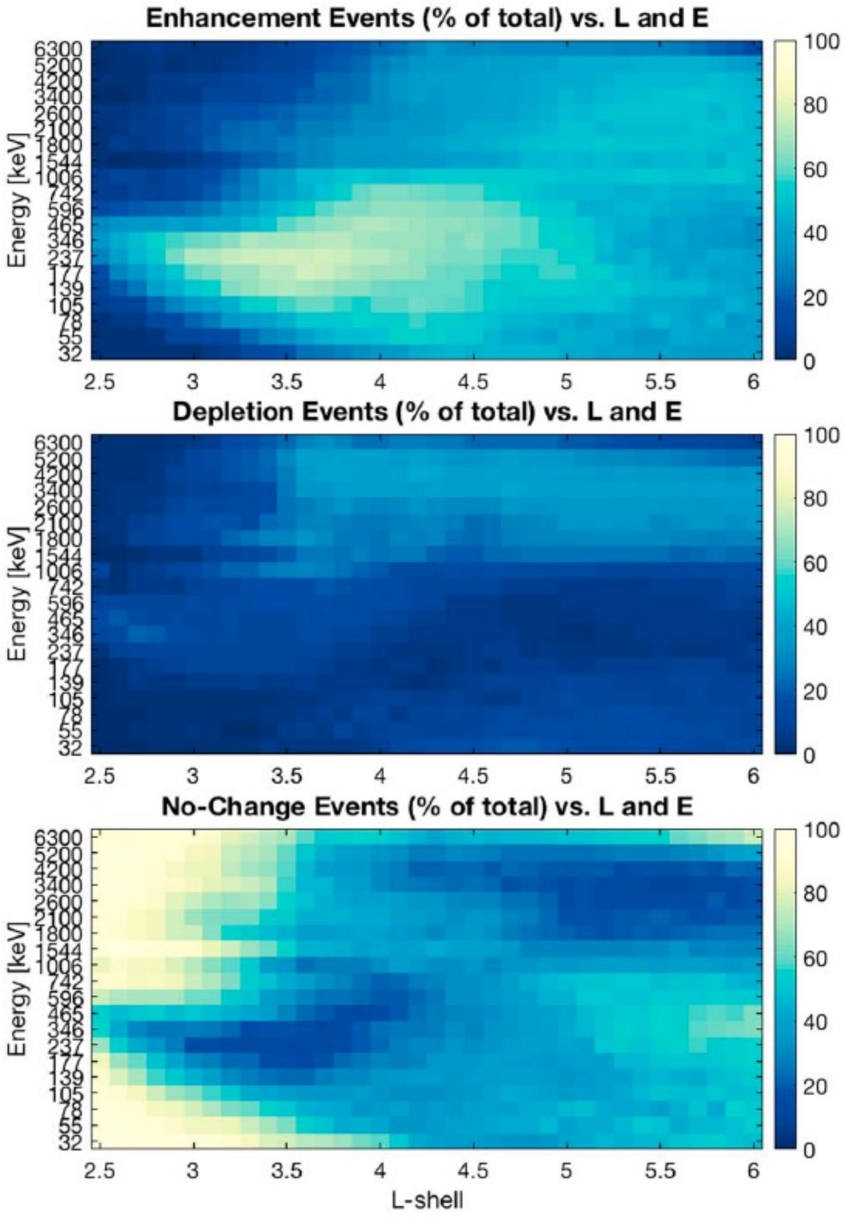


Turner et al., JGR 2019

$$R = \frac{\max(\text{pre} - \text{event flux})}{\max(\text{post} - \text{event flux})}$$

$R > 2$: enhancement

$\frac{1}{2} < R < 2$: no-change

$R < 2$: depletion

Source & Seed: typically enhance or no-change likely due to the refilling by substorm injections, convection and subsequent chorus acceleration

Core & ultra-relativistic: In the inner parts of the outer belt no change dominates. In the outer parts of the outer belt most events enhance (~50 %) or deplete (~30%)



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# Let's start to then look how the response is if we divide them by the driver.



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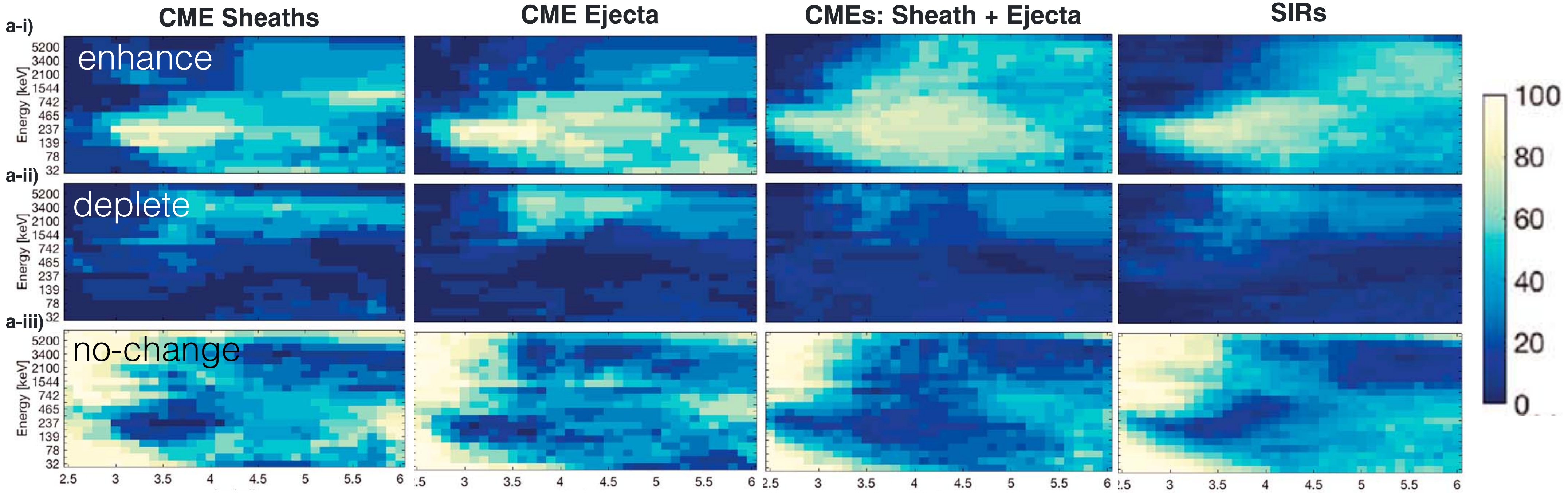


Turner et al., JGR 2019

Ejecta & sheaths: deplete > 1 MeV electron fluxes at L > 3. They cause strong enhancements at seed energies in the hearth of the outer belt around L = ~3 - 4.

Sheath + Ejecta: likelyhood of the enhancement increases for high energies and L – shells ≳ 3

SIRs:  enhance also high energies, but the enhancement starts from L = 4 (consistent with Shen et al., 2017 that CME-driven storms enhance more > 1 MeV electrons at the heath of the belt)




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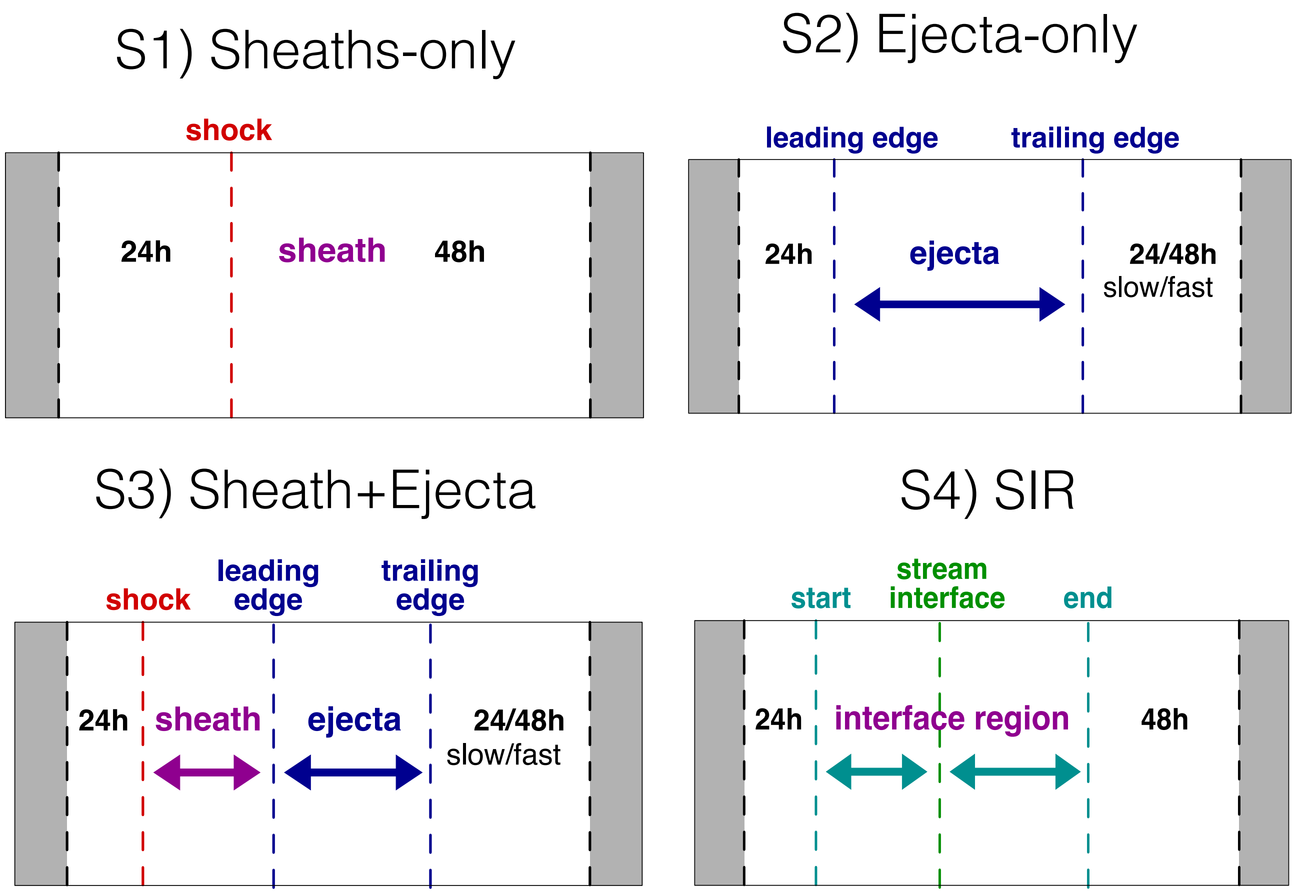


Solar wind structures divided into above four categories

Kilpua et al., 2015

Focus on structured solar wind drivers. The data were superposed and renormalized.

193 isolated storms over 1995 – 2013 with Dst < -50 nT. GOES > 2 MeV electron fluxes

This approach emphasizes solar wind context.



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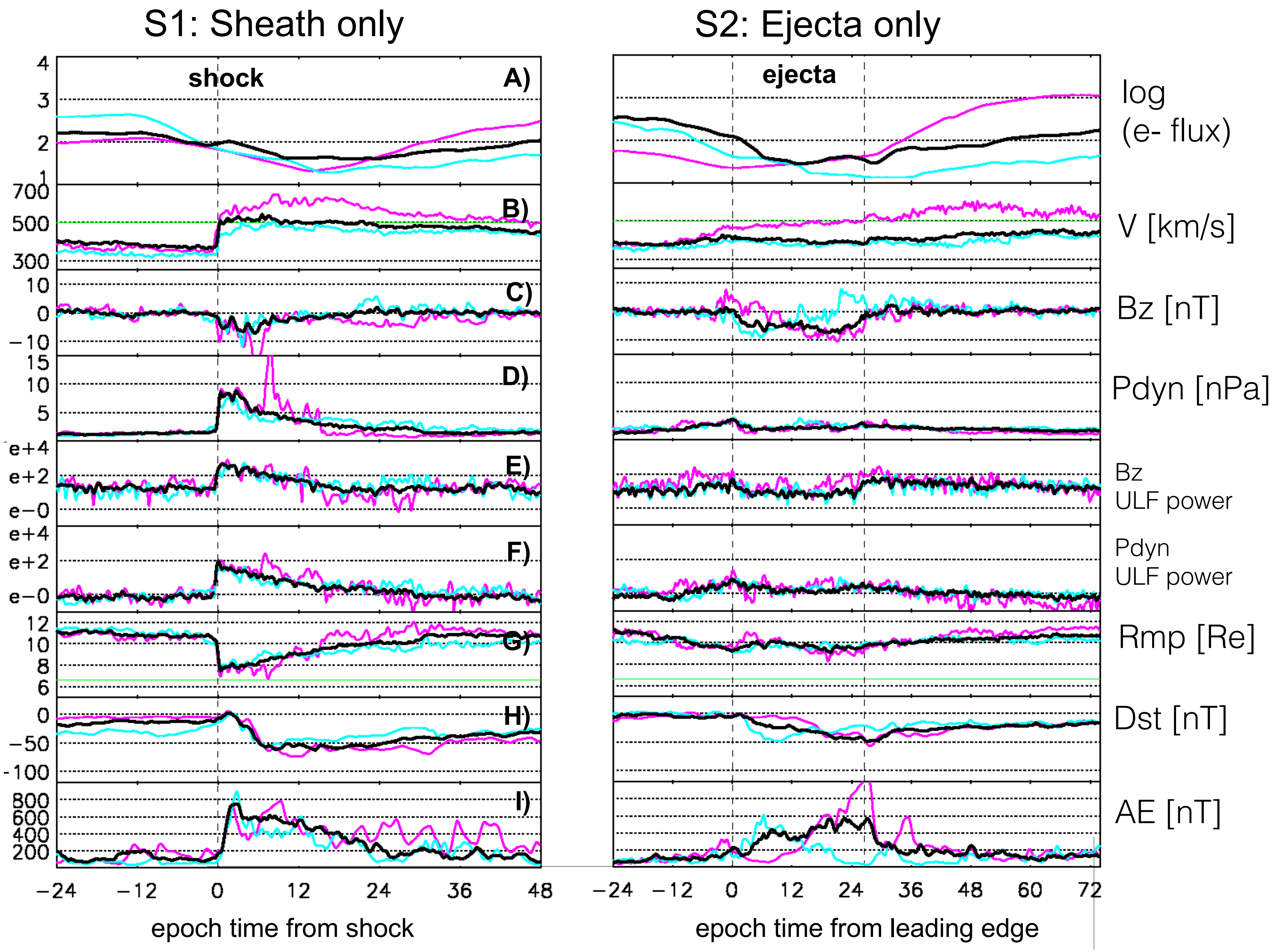


Enhance
Deplete
All

Kilpua et al., 2015



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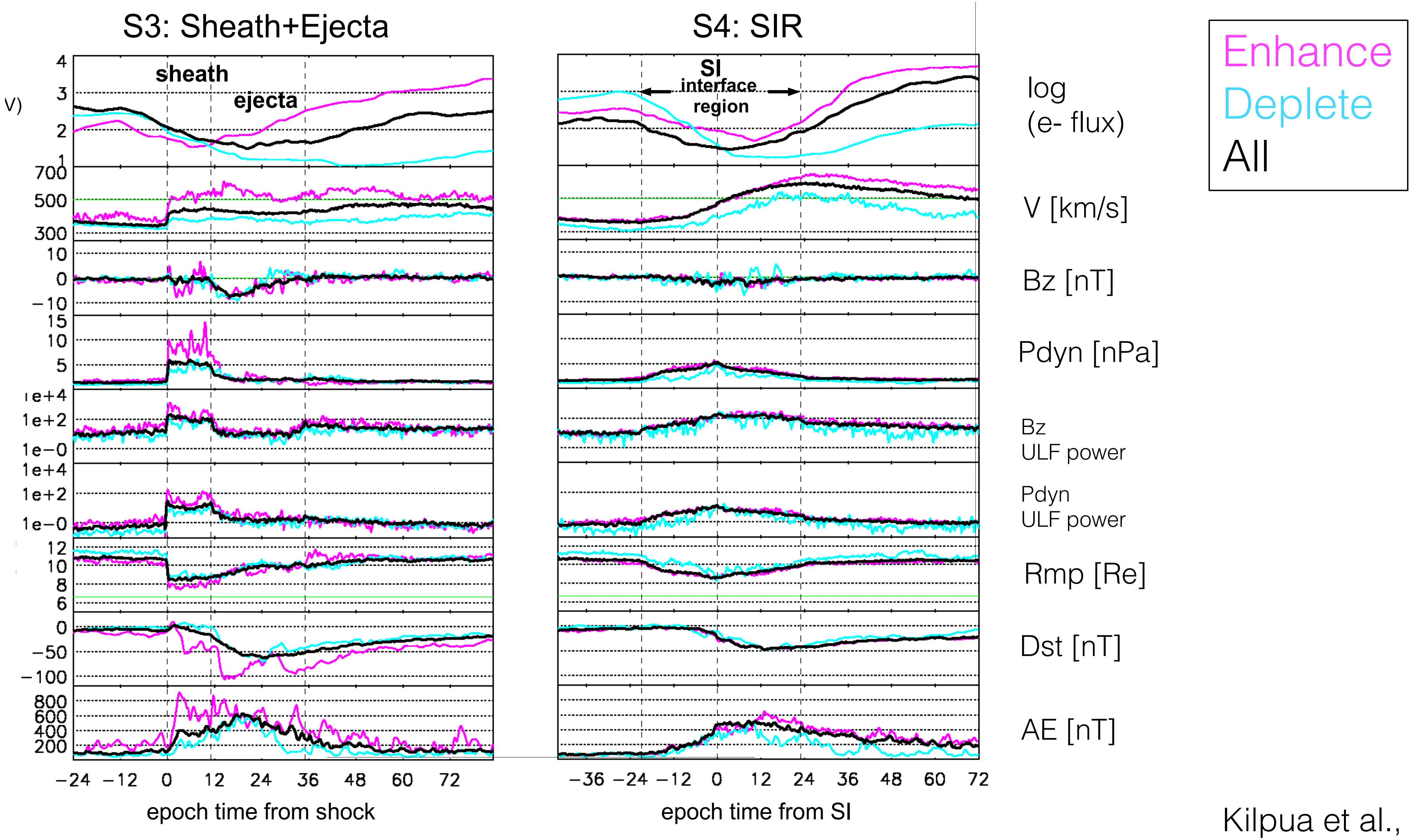


Kilpua et al., 2015




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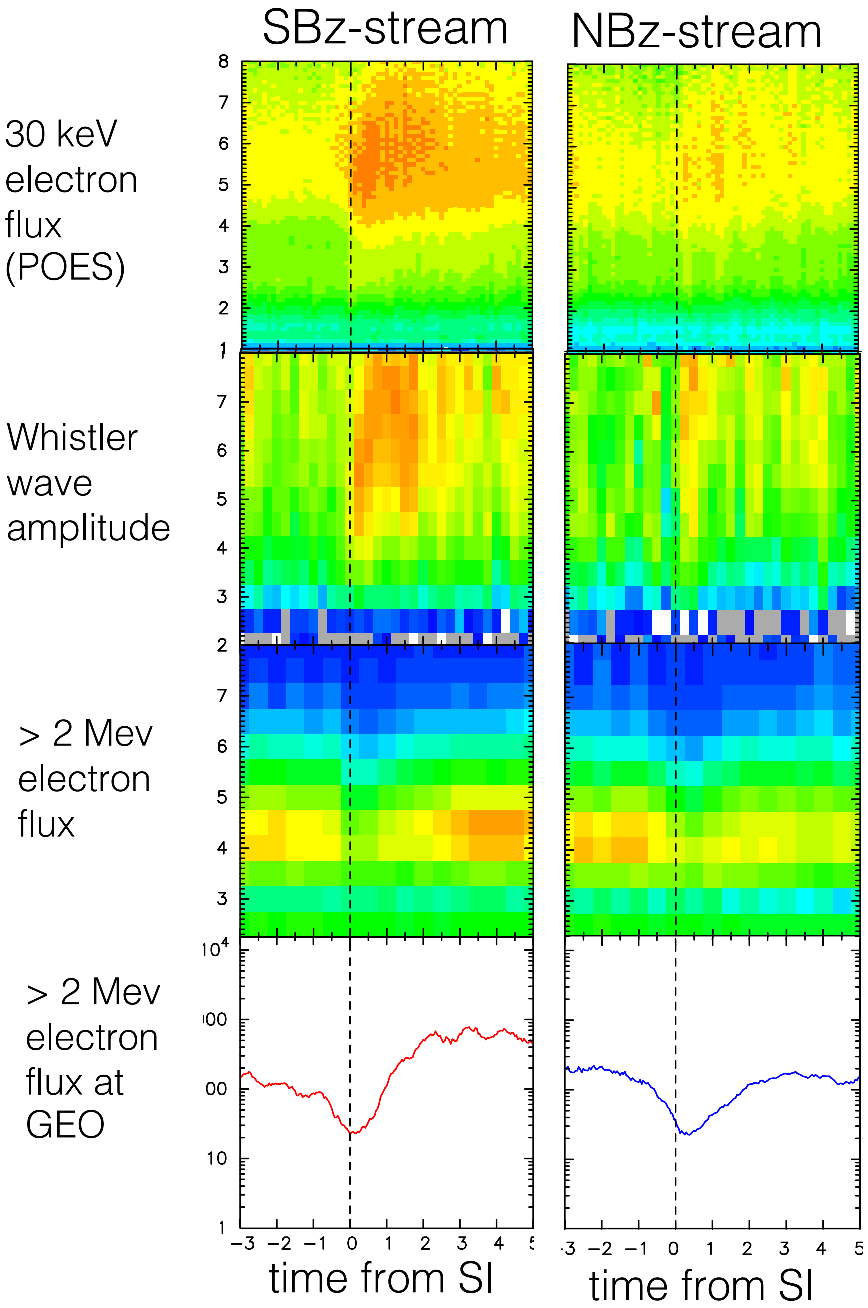


# Fast streams with southward IMF (SBz) cause > 2 MeV electron flux enhancement at the geosynchronous orbit.

SBz streams cause substorms that effectively inject source electrons and seed electrons → chorus waves → progressive acceleration to higher energies (e.g., Jaynes et al., 2015)

Miyoshi et al., 2013




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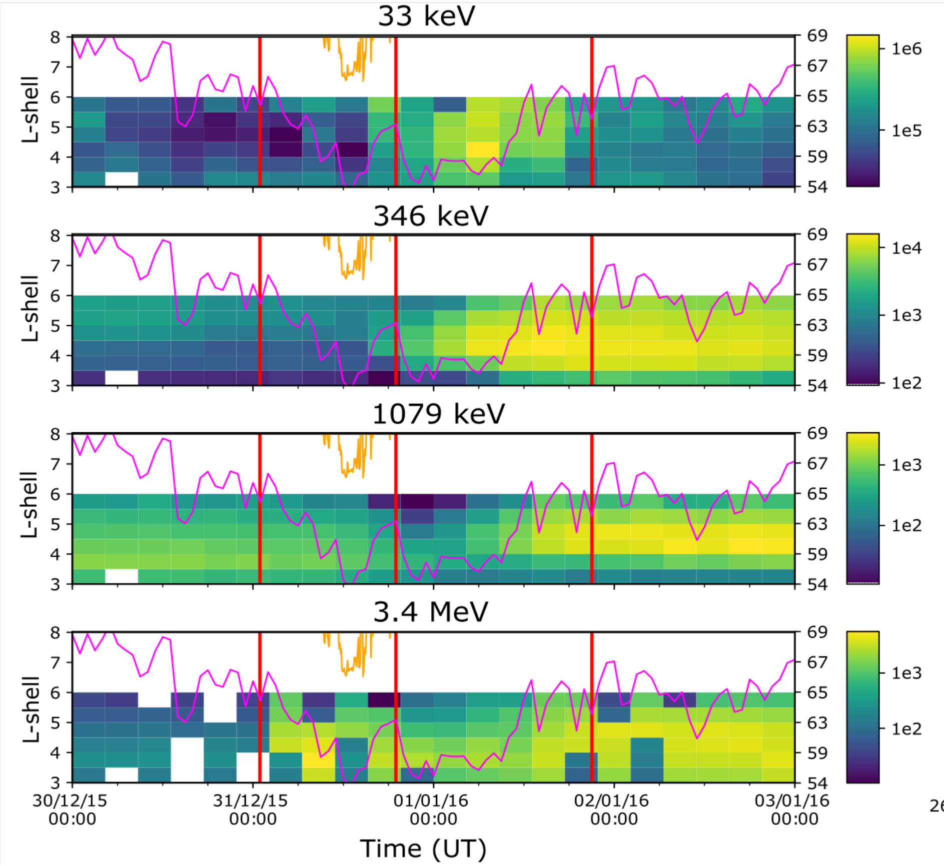
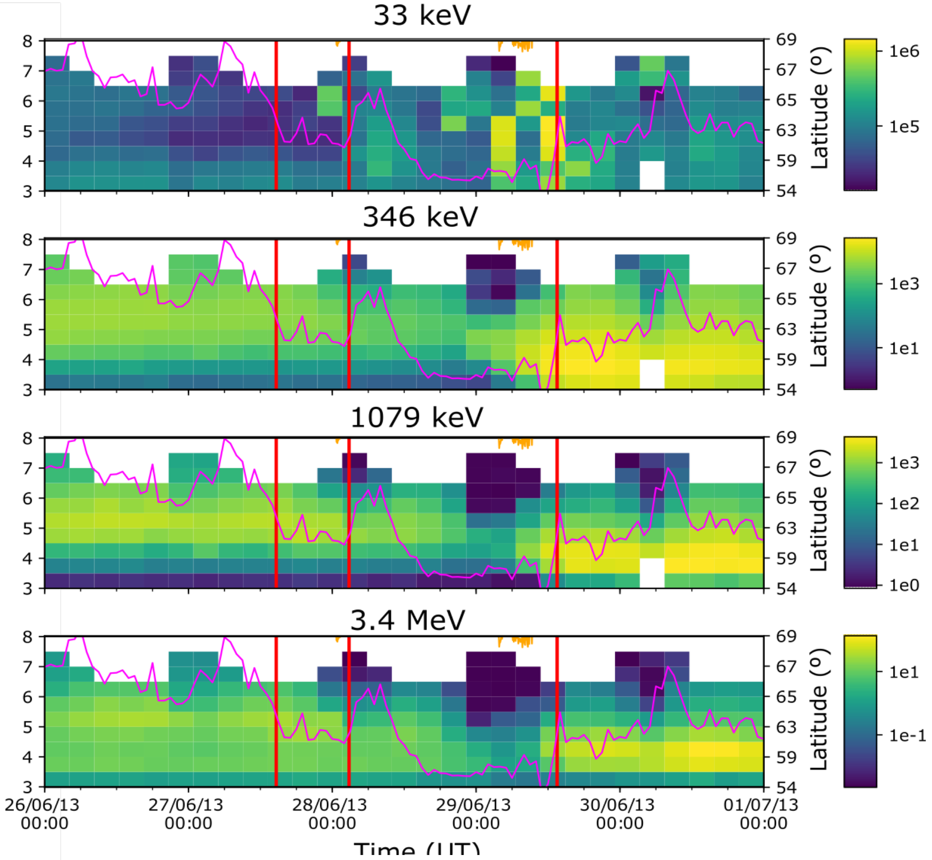
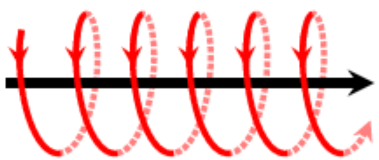
# Radiation belt electron flux response

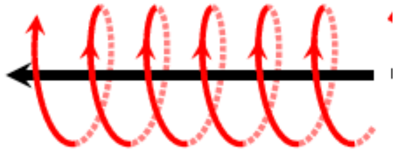
## Dec 2015: South-north magnetic cloud




## June 2013: North-south magnetic cloud





George et al. 2019



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Solar wind conditions can vary relatively rapidly. It is interesting to look more immediate response (here for the sheaths)




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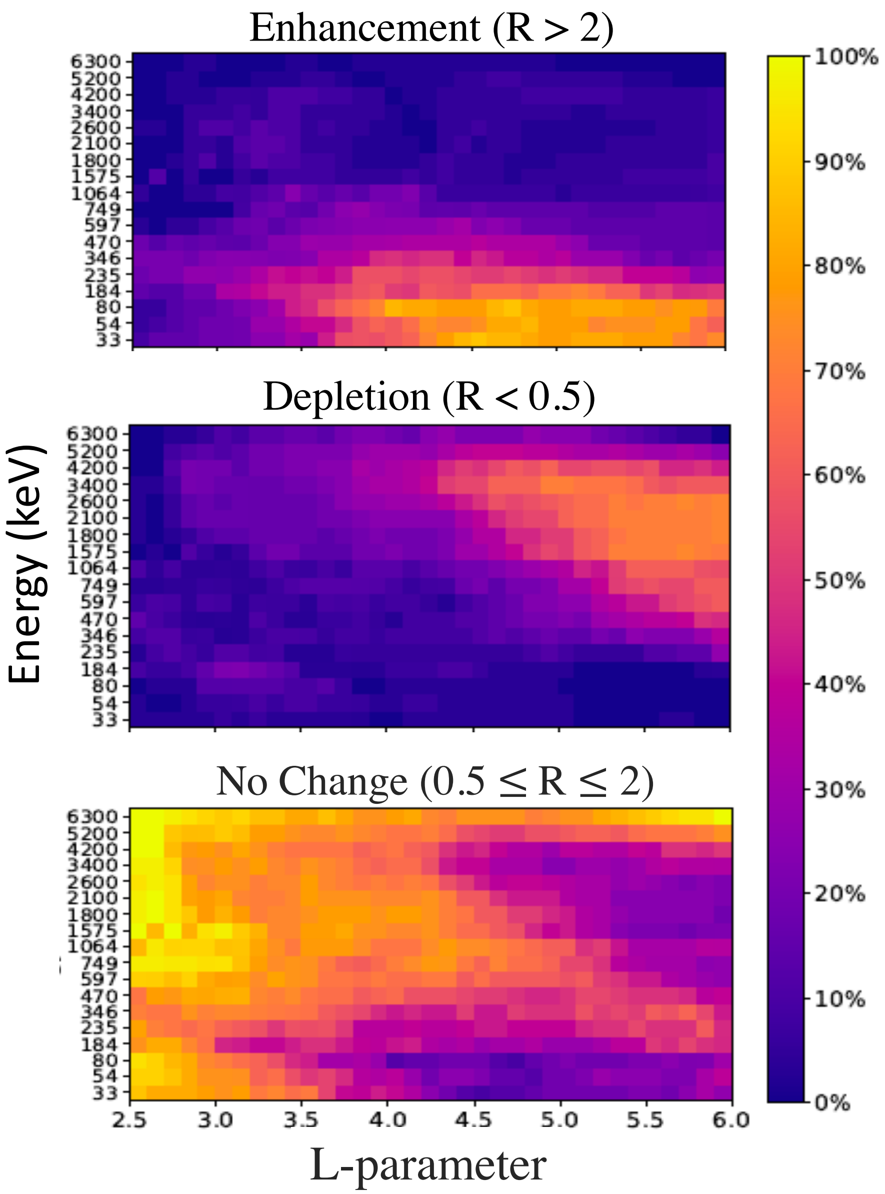


Kalliokoski et al. 2019

$$R = \frac{\langle \text{flux} \rangle_{after}}{\langle \text{flux} \rangle_{before}}$$

$\langle \text{flux} \rangle_{before}$ : average 6 hrs before the shock

$\langle \text{flux} \rangle_{after}$ : avergage 6 hrs after the sheath

Source: enhances practically in every storm at L > 4 (substorm injections)

Seed: population enhances in about 50% of cases (otherwise no-change) at L > 4

Core and ultrarelativistic: nearly always deplete at L > 4.5. At L = 3.5 they enhance in about 20-30% of cases

Depletion progresses to lower energies with increasing L → energy-dependent wave-particle interaction at lower L and magnetopause shadowing at higher L

← 37 sheath-driven storms 2012-2018. No constrain for the strength of the storm!



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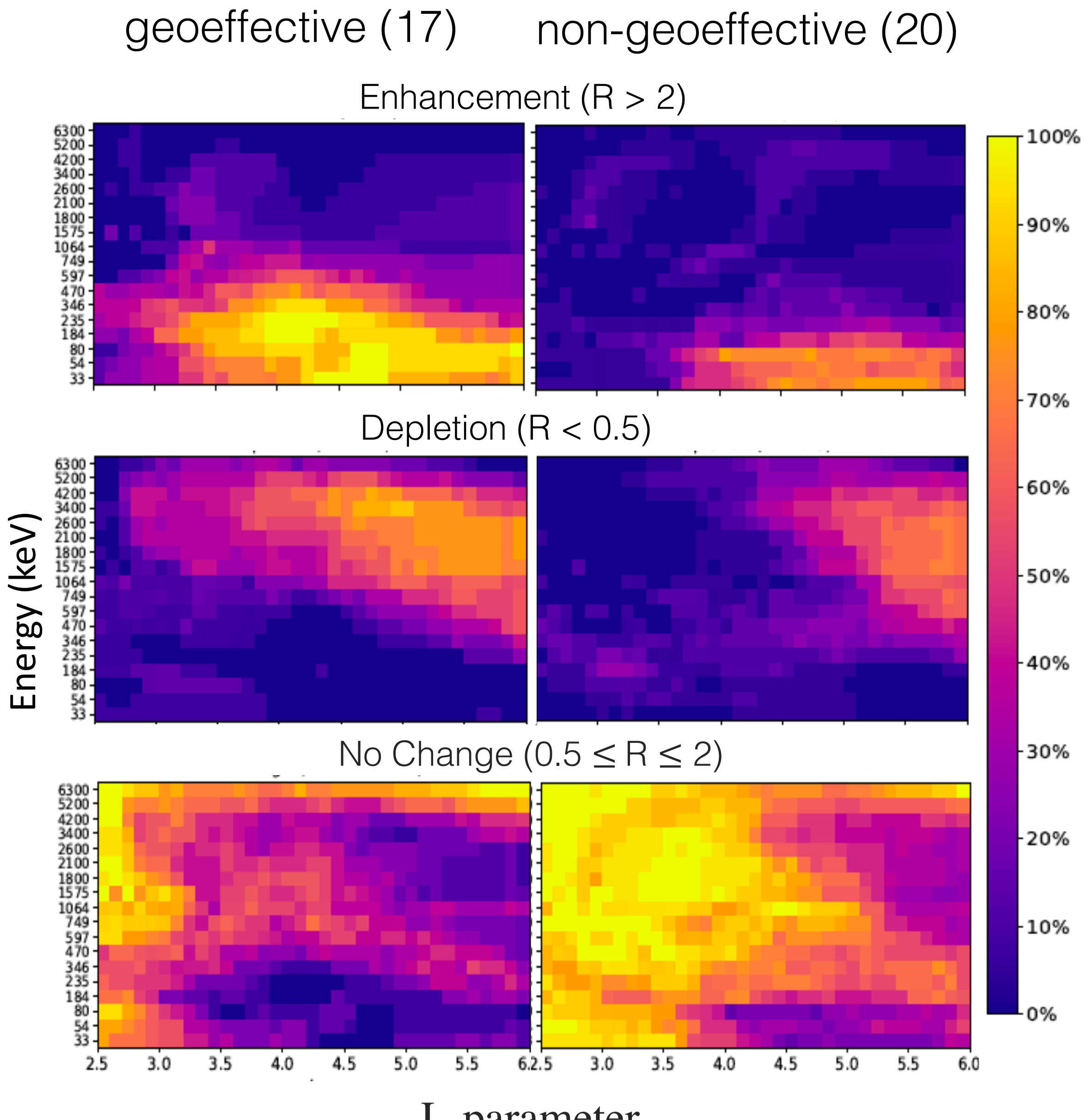


Kalliokoski et al. 2019

**Geoeffective sheaths**: enhance more often, at higher energies and to lower L-shells

**Non-geoeffective sheaths**: leave the lower L-shells mostly intact. At high L-shells high energies deplete , lower enhance

→ Non-geoeffective sheaths also disturb the belts dramatically (deplete)!



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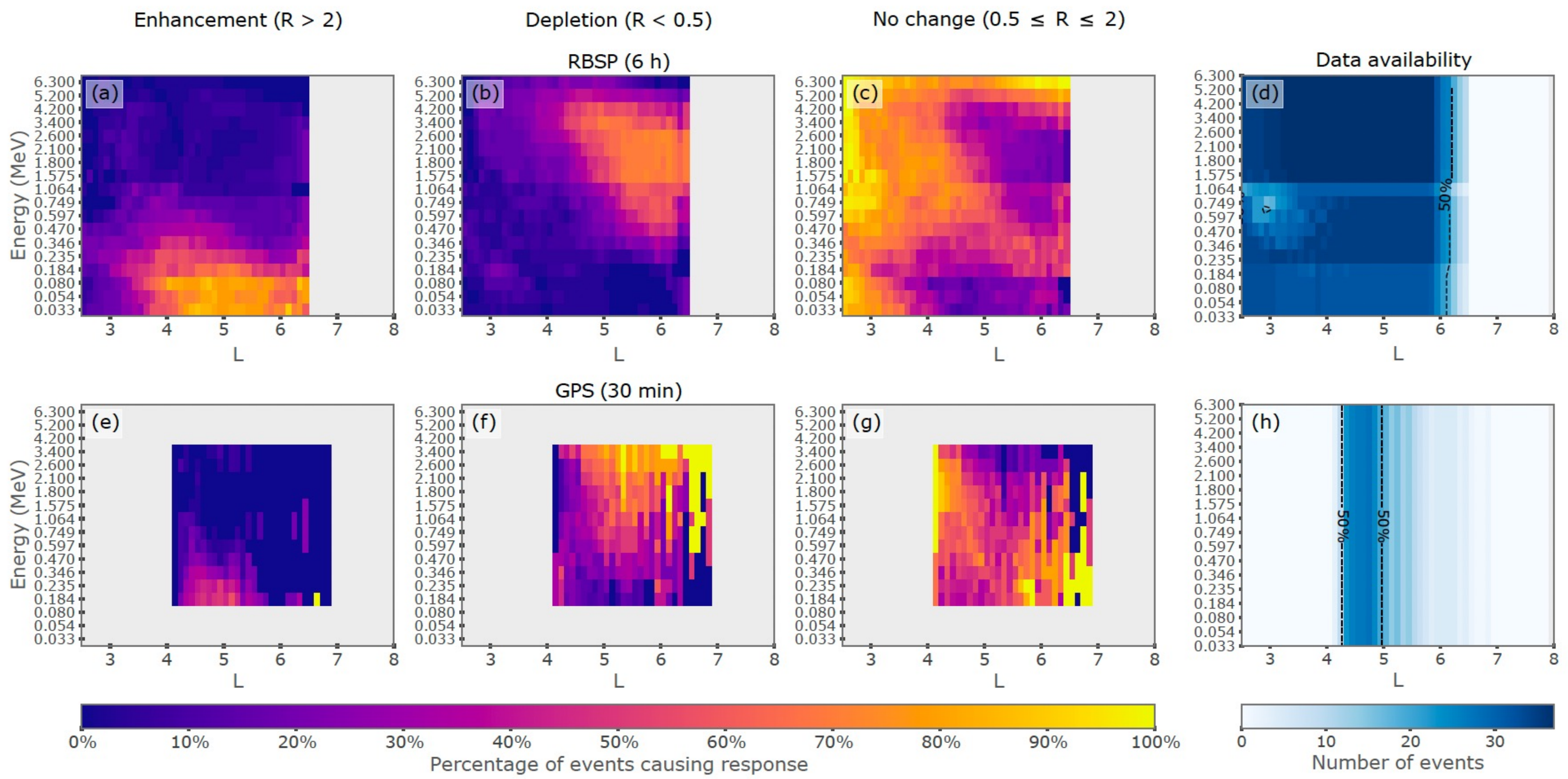


Kalliokoski et al. in revision

GPS data allow detecting changes in much higher time resolution (even more immediate sheath response). Phase Space Density (PSD) analysis separates adiabatic and non-adiabatic effect. See poster by Milla!

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# What controls the response? A: Inner magnetospheric waves



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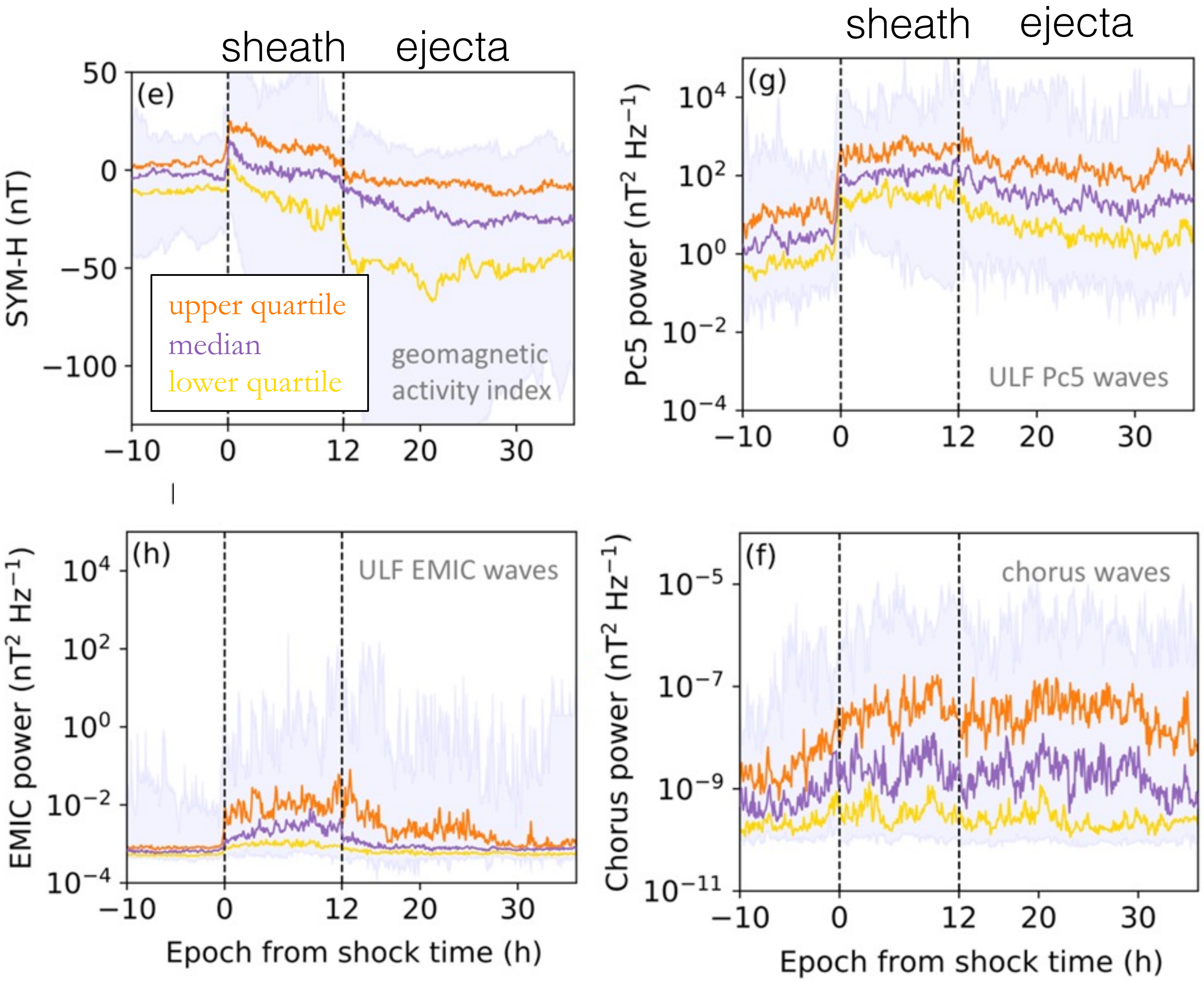


Sheaths in this data set are clearly less geoeffective than ejecta in terms of SYM-H (ring current), but induced similar level or higher wave activity in the inner magnetosphere

← 37 Sheath that were sampled to the same average duration (10.2 hours)



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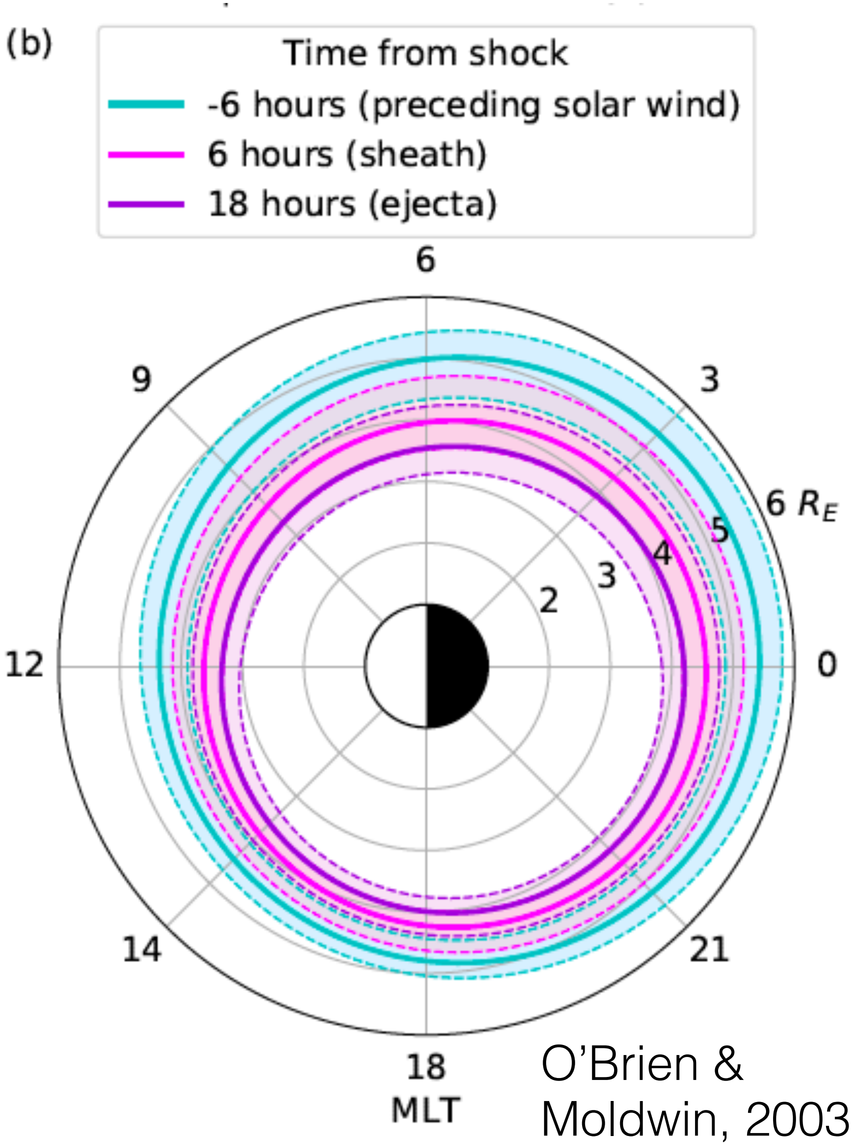


O'Brien & Moldwin, 2003 model

Kalliokoski et al. 2019

The wave-particle interactions depend strongly on whether particles are inside or outside the plasmasphere

Plasmapause is located closest to the Earth during the ejecta (strong convection)

During the sheath a bit further, but closer to the Earth than in the preceding (quiet) wind

Remember! location depends strongly on geomagnetic activity



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# What controls the response?
# B: Magnetopause shadowing



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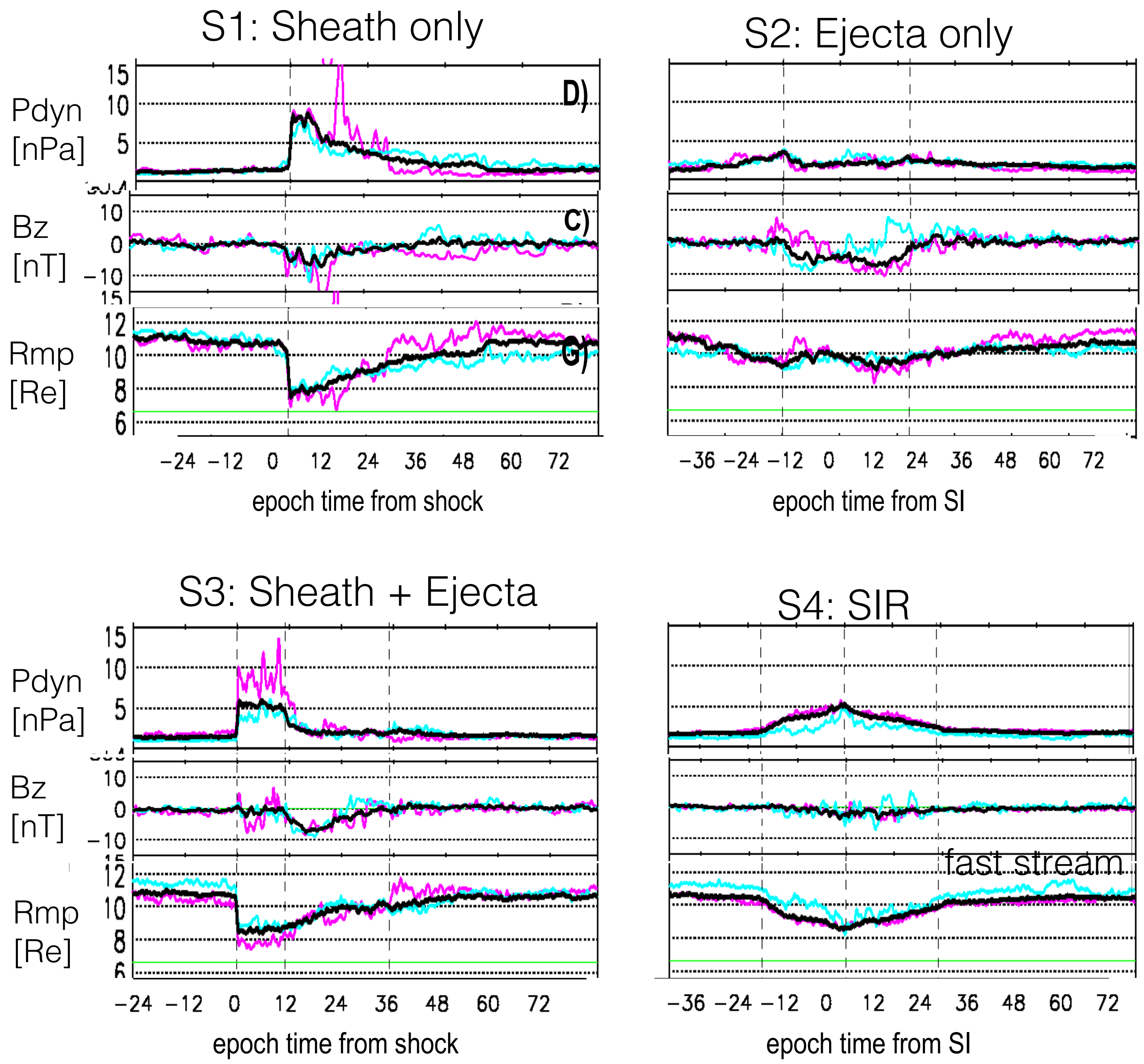


Different drivers have different southward field characteristics and dynamic pressure

→ Clear differences in magnetopause shadowing expected

Sheaths and SIRs compress the most, Ejecta mainly erode, fast streams have magnetopause close to nominal position



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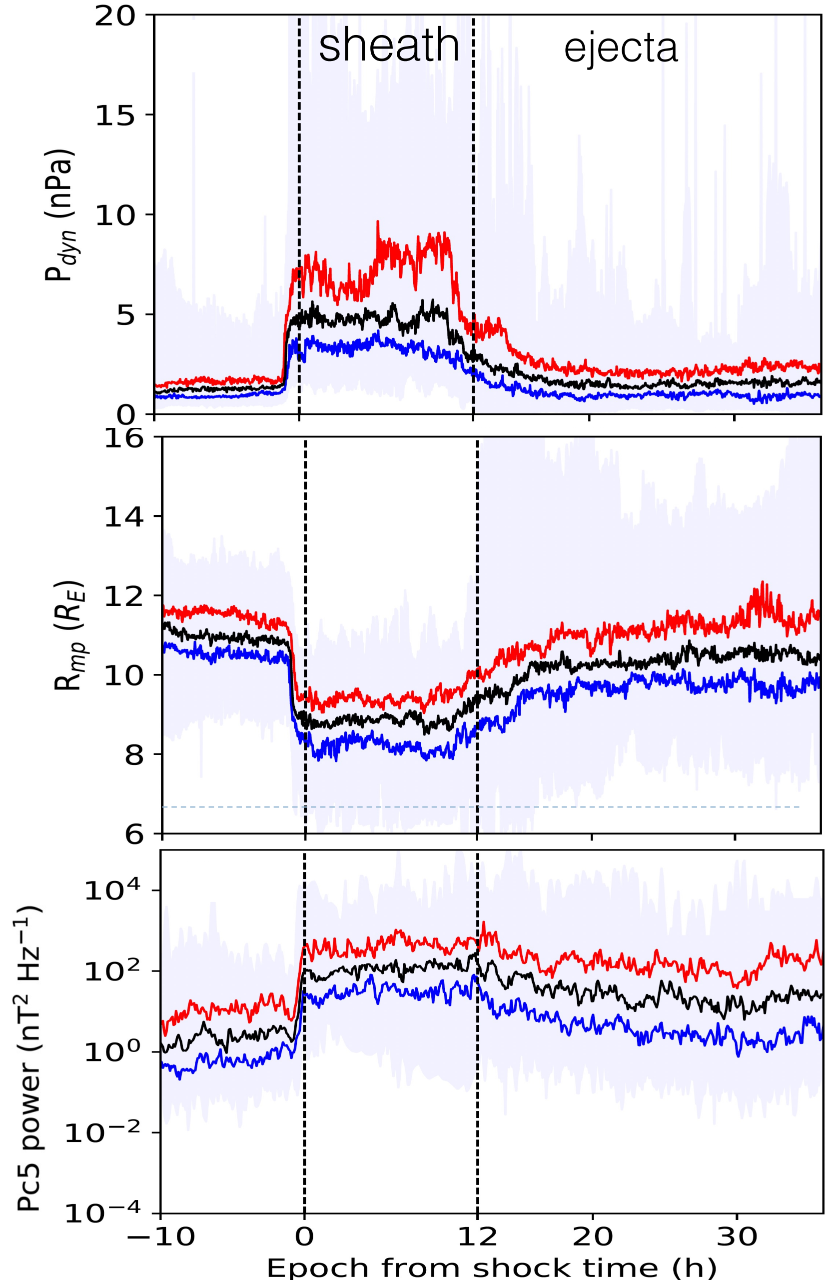


High dynamic pressure in the sheath region compresses strongly the MP, occasionally even beyond geostationay orbit.

Losses are enhanced due to high ULF Pc5 wave activity → enhanced outward transport

During the ejecta the magnetopause typically relaxes towards the nominal position (dynamic pressure and also Pc5 activity wanes)

Kalliokoski et al. 2019




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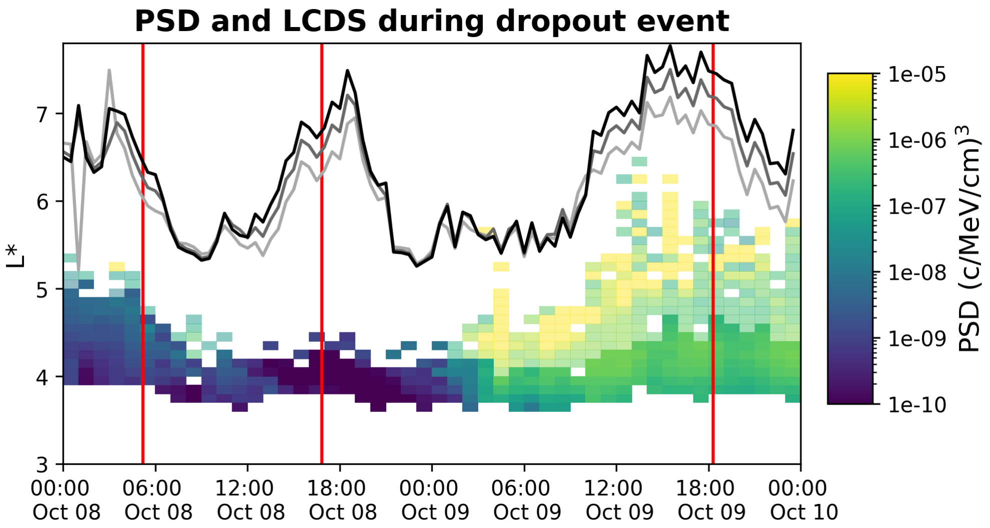
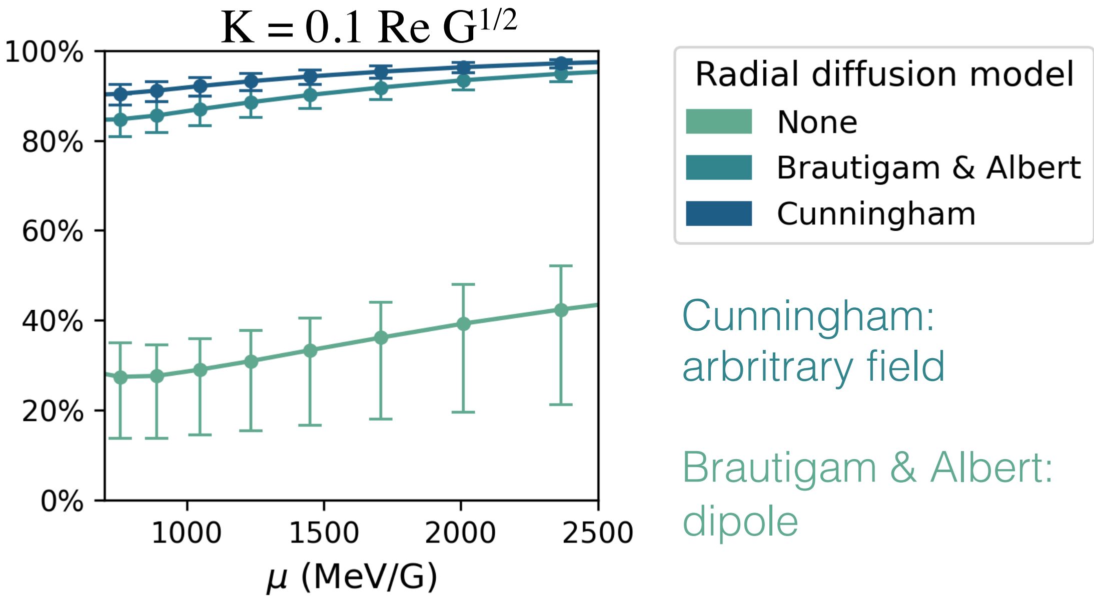
# October 2012 sheath electron dropout event




Cunningham: arbitrary field

Brautigam & Albert: dipole

To evaluate the losses from the outer radiation belt, it is critical to consider radial diffusion (up to 70% difference). In addition, it is important to consider the non-dipolar magnetic field configuration (up to 10% differnece)

George et al., in revision



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| Driver | Outer radiation belt response | Key mechanism(s)* |
| --- | --- | --- |
| Shock | Rapid acceleration of MeV electrons in the heart of the belt (quickly lost when the sheath arrives) | Shock launches a compressional magnetosonic impulse that causes drift resonance of high energy electrons |
| Sheath | Sustained and deep depletions at wide range of energies and L. Source and seed energies enhance throughout the outer belt. Geoeffective sheath's effect extends clearly deeper in the outer belt. | Losses cause by the MP shadowing (outward transport + MP compression). Intense wave activity that both scatter and energize |
| Ejecta | Deplete at high L–shells. Source and seed energies enhanced throughout the belt. | Magnetopause inward due to erosion + Dst effect |
| SIR | Deplete the belts (up to at least Stream Interface) | Same as for sheaths but less pronounced |
| Fast stream | Enhance (in particular at high L–shells) | Propgressive acceleration by chorus waves, lack of conditions favoring losses |

*most studies look storms only. Enhancement at core and seed caused by substorm injections replenishing those populations.



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