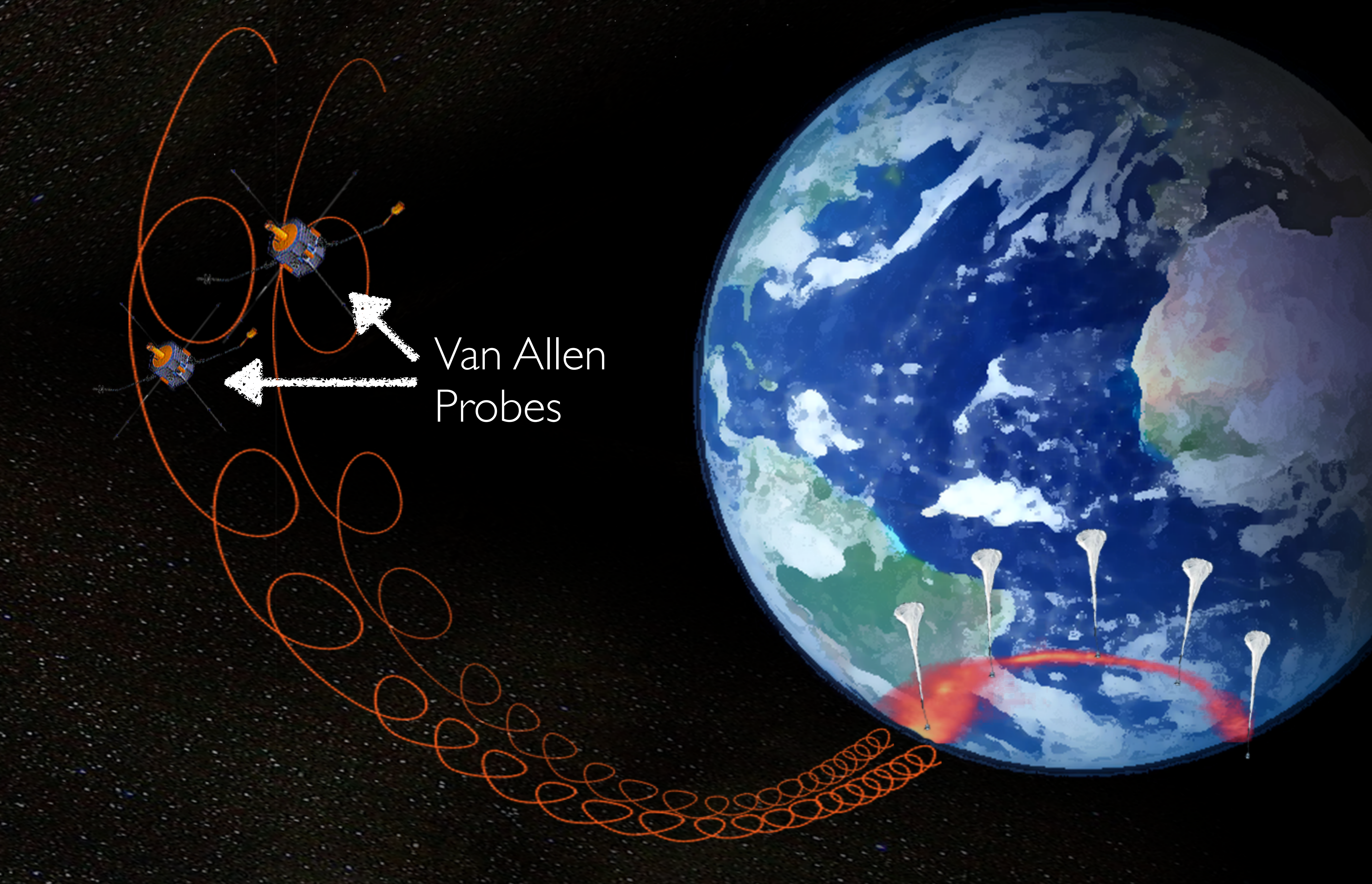
What have we learned from BARREL?

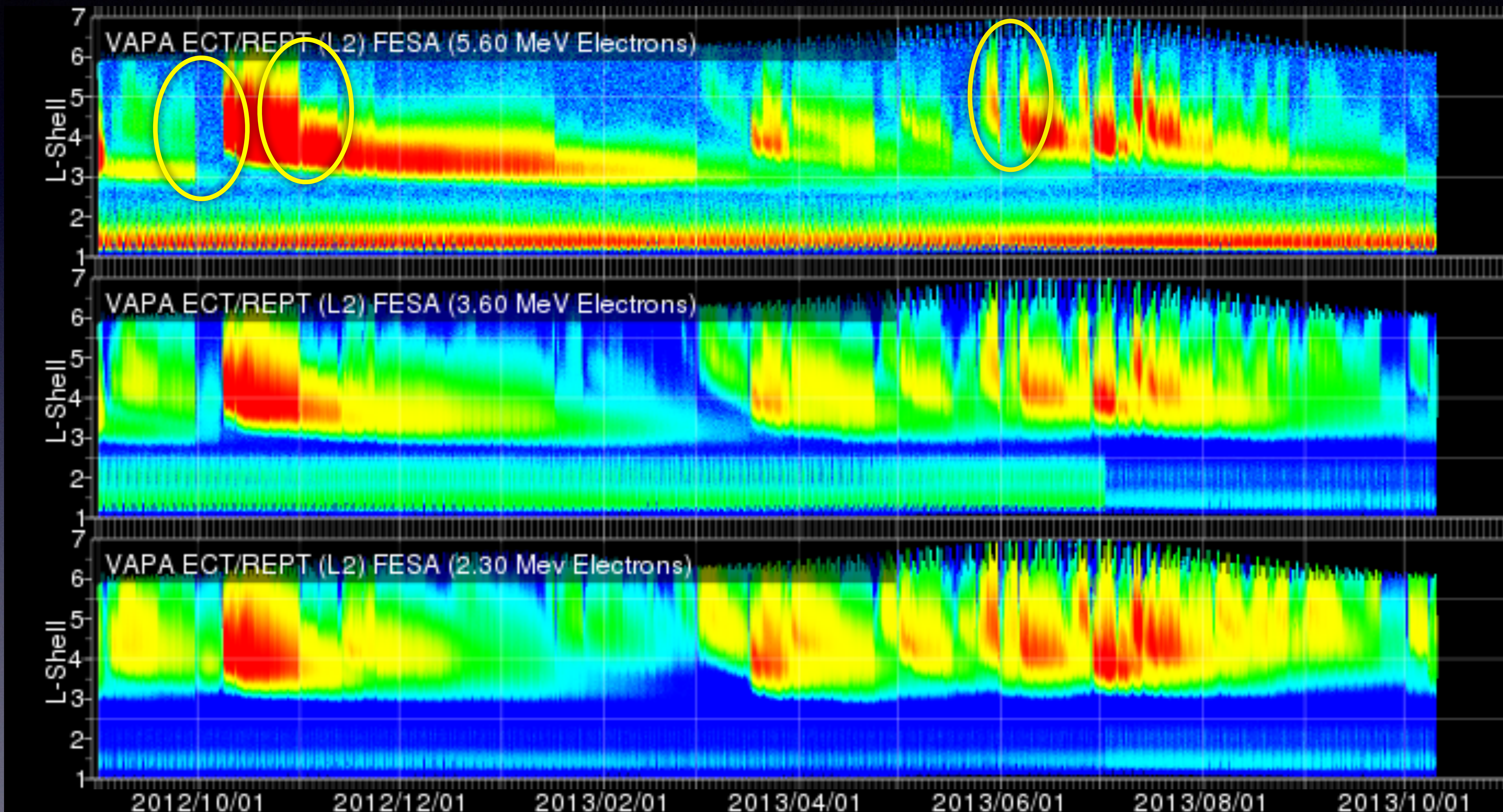
R. M. Millan
and the BARREL Team

Balloon Array for Radiation belt Relativistic Electron Losses



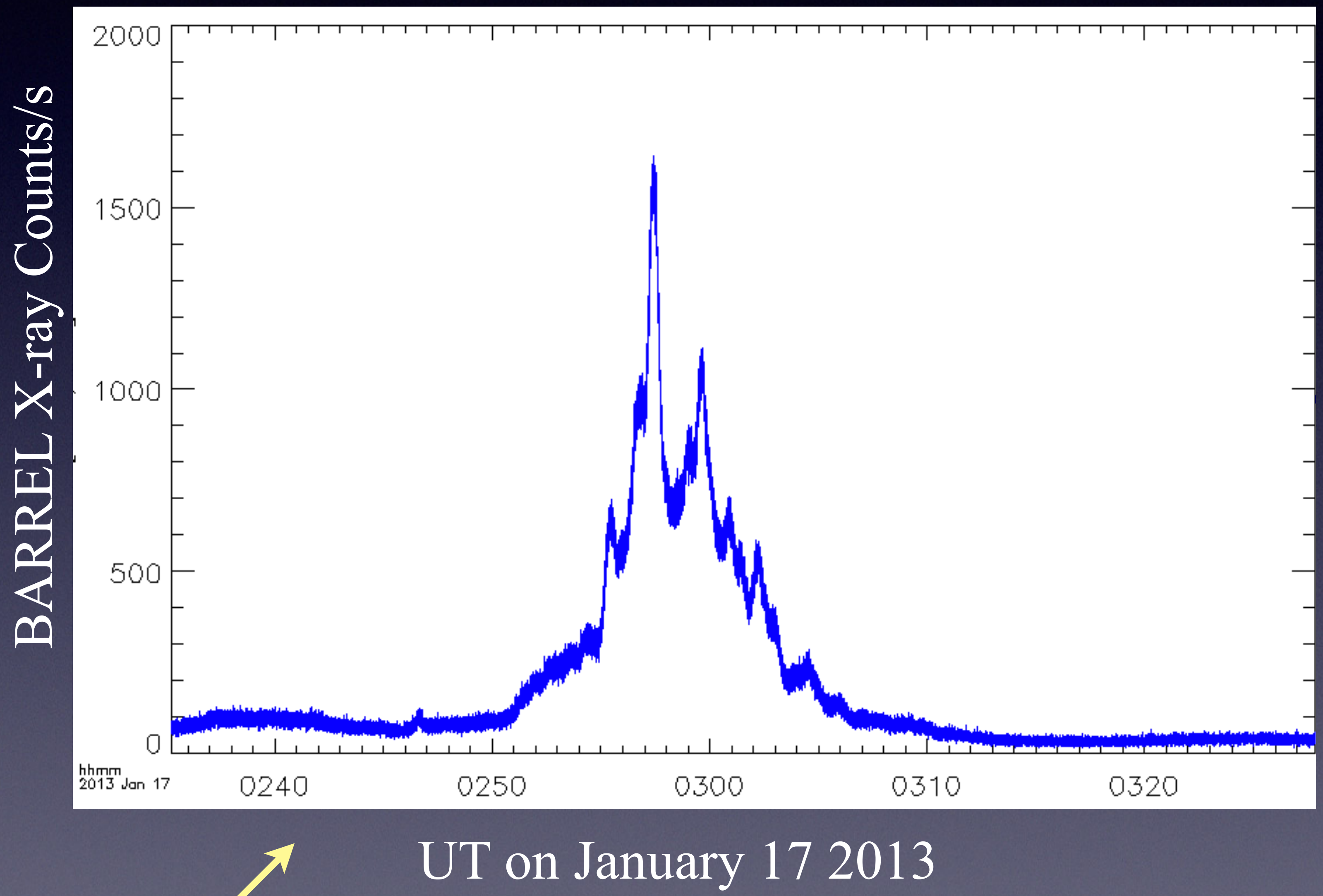
Radiation Belt Depletions

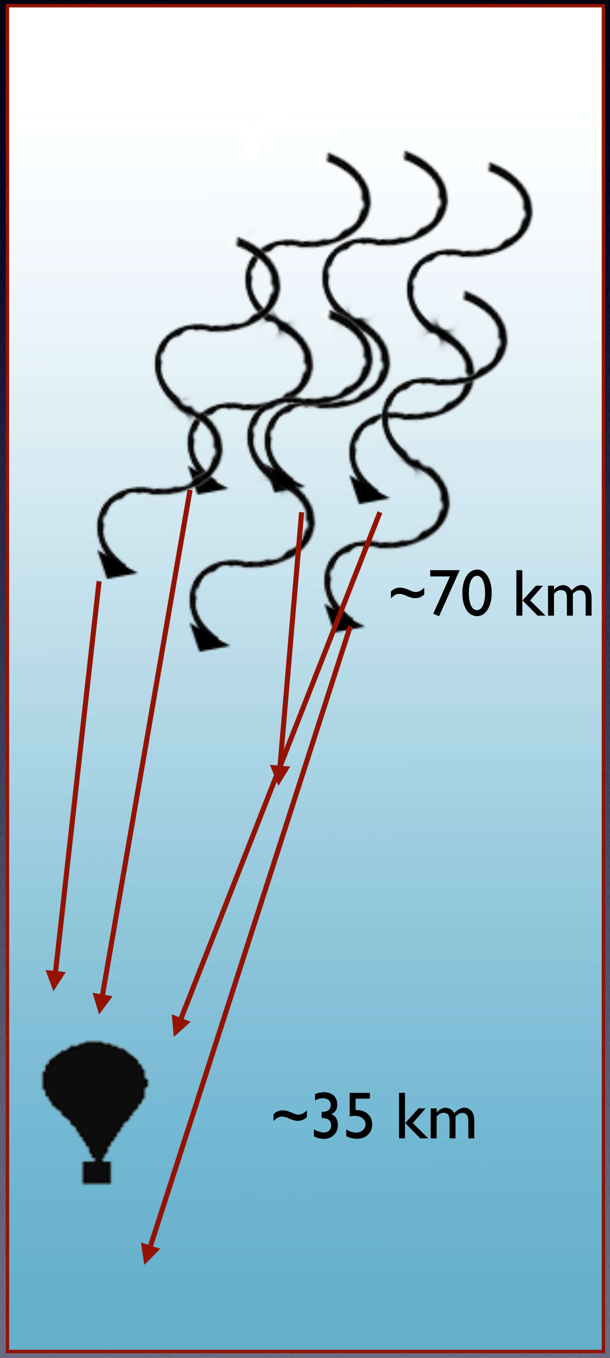
Where do the electrons go?



Balloon Observations of Electron Precipitation

- Bremsstrahlung X-rays are produced as electrons collide with atmospheric neutrals.

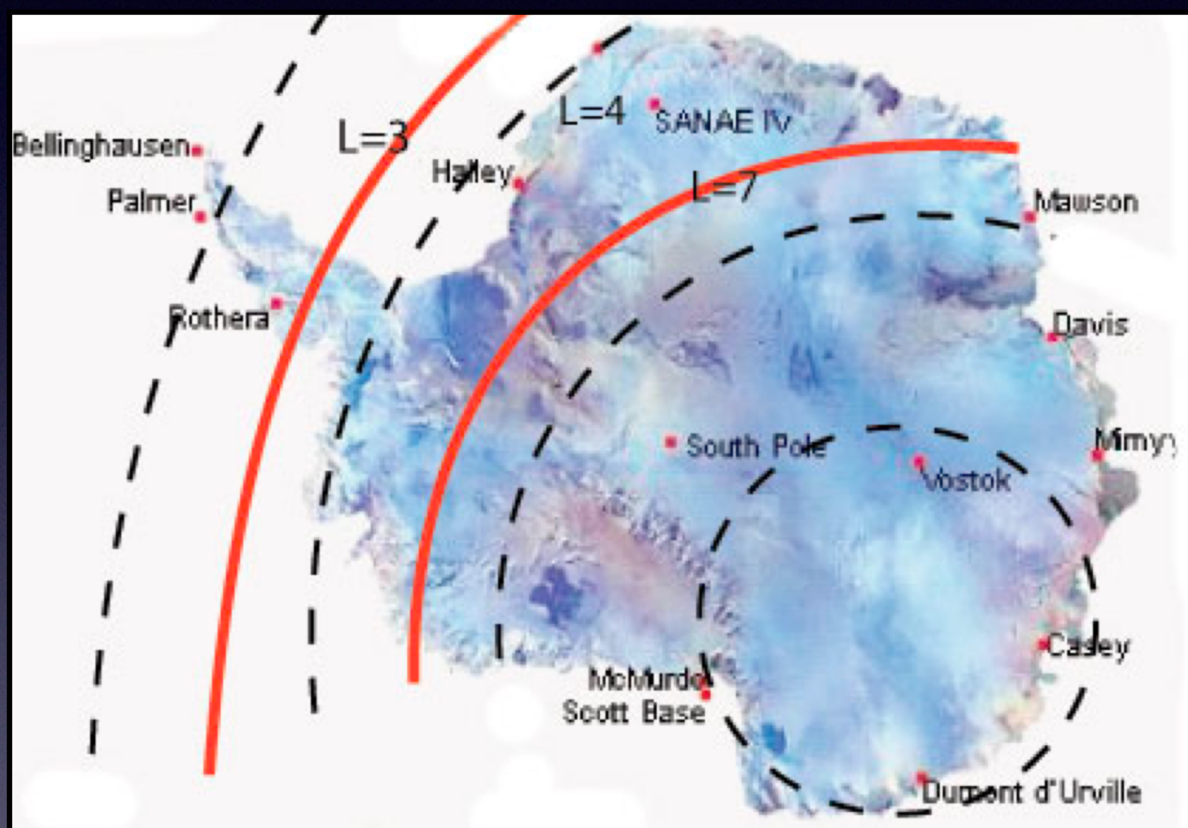




Relativistic electron precipitation event detected during 2013 BARREL campaign

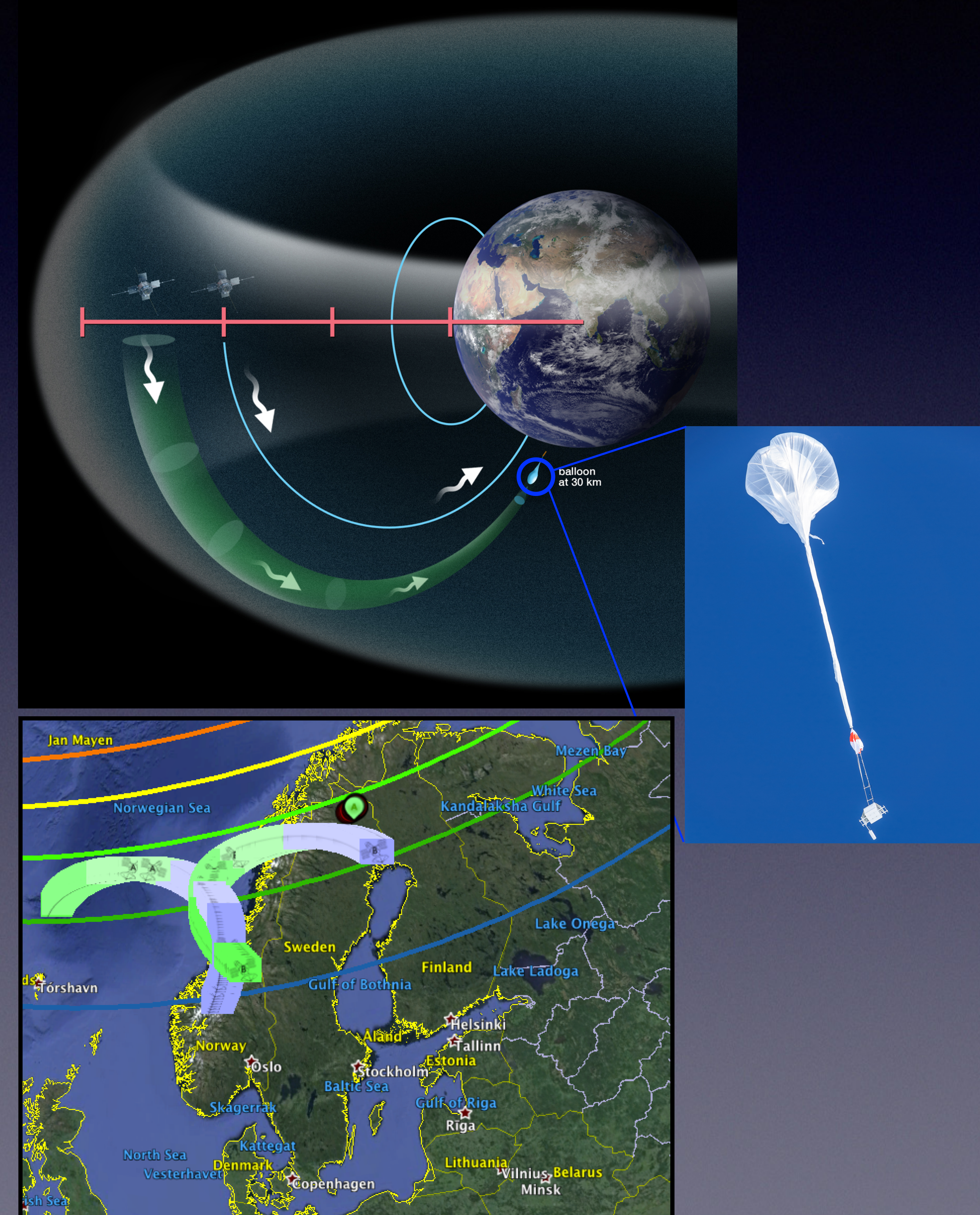
BARREL Mission Design

- Two Antarctic Campaigns
  - array of 5-8 balloons aloft
  - average duration ~12 days
  - 20 balloons per campaign



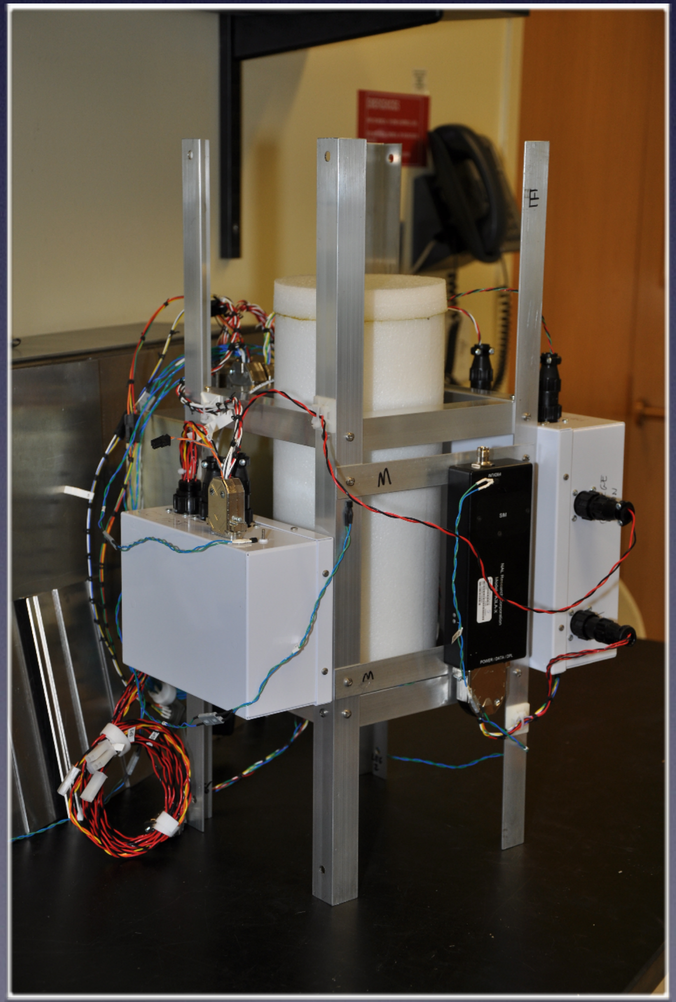
- Two Sweden Campaigns
  - launched from Esrange, Sweden
  - Turnaround flights ~1-2 days
  - 1 or 2 balloons aloft

Magnetic conjunctions with Van Allen Probes



BARREL Instrumentation

- Primary Instrument: 3”x3” NaI scintillator
  - Measures X-rays: 20 keV - 10 MeV
  - Time and Energy resolution:
    - 50 ms in 6 channels 20-1500 keV
    - 4 s in 48 channels 100 keV-4 MeV
    - 32 s in 256 channels 20 keV-10 MeV



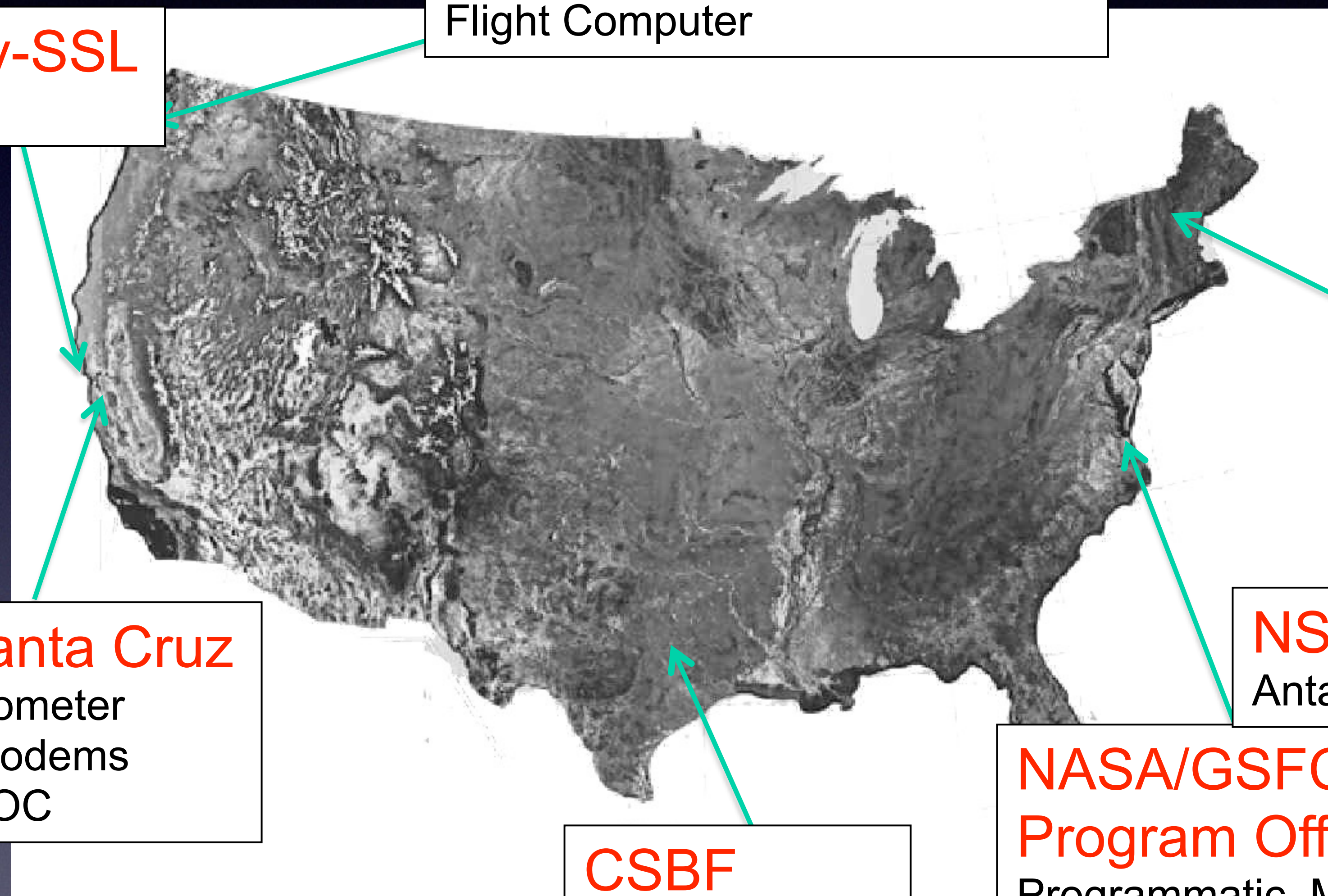
- Built 45 Payloads
  - Suspended mass: 25 kg (payload ~20 kg)
  - Power: ~5W supplied by solar
  - Telemetry: Iridium satellite network (~2 kbits/s)
  - Hand launched on 300,000 cu ft. balloon

BARREL Campaign Summary

- 55 science payloads launched during four balloon campaigns:
  - January - February 2013 and 2014 (Antarctica)
  - August 2015 and 2016 (Sweden)
- Coordinated Observing Campaigns
  - Van Allen Probes
  - Cubesats: CSSWE, FIREBIRD, AC-6
  - MMS
  - EISCAT and other ground-based
  - ABOVE2 balloon project
- 2018 Sweden piggyback flight

For more information about BARREL:
- Millan et al., 2013 (SSR)
- Woodger et al., 2015 (JGR)

BARREL Collaboration



University of Washington
NaI Scintillator
Flight Computer

UC Berkeley-SSL
Power System

Dartmouth College
PI-Institution
Systems Engineering
Engineering Data
Terminate System
Mechanical, Harness
Integration & Test

NSF
Antarctic logistics, coordination

UC Santa Cruz
Magnetometer
Flight modems
MOC/SOC

CSBF
Phase B Flights
Launch Training

NASA/GSFC + Balloon Program Office
Programmatic, Management oversight

Campaign and science support

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

South African National Antarctic Programme
SANAP
understand, develop, conserve

SSC

BARREL Science Objectives

- Determine electron loss rate during relativistic electron events
- Directly test models of wave-particle interactions
- Determine spatial extent and large-scale structure of precipitation.
- Determine relative importance of different types of precipitation

BARREL Bibliography

1. Millan, R.M. (2011), Understanding relativistic electron losses with BARREL, Journal of Atmospheric and Solar- Terrestrial Physics, doi: 10.1016/j.jastp.2011.01.006
2. Millan, R. M., et al. (2013), The Balloon Array for RBSP Relativistic Electron Losses (BARREL), *Space Science Reviews*, doi:10.1007/s11214-013-9971-z.
3. Blum, L. W., Q. Schiller, X. Li, R. Millan, A. Halford, and L. Woodger (2013), New conjunctive CubeSat and balloon measurements to quantify rapid energetic electron precipitation, Geophys. Res. Lett., 40, 58335837, doi:10.1002/2013GL058546.
4. Li, Z., R. M. Millan, M. K. Hudson, L. A. Woodger, D. M. Smith, Y. Chen, R. Friedel, J. V. Rodriguez, M. J. Engebretson, J. Goldstein, J. F. Fennell, and H. E. Spence (2014), Investigation of EMIC wave scattering as the cause for the BARREL 17 January 2013 relativistic electron precipitation event: A quantitative comparison of simulation with observations, Geophys. Res. Lett., 41, 87228729, doi:10.1002/2014GL062273.
5. Woodger, L. A., A. J. Halford, R. M. Millan, M. P. McCarthy, D. M. Smith, G. S. Bowers, J. G. Sample, B. R. Anderson, and X. Liang (2015), A summary of the BARREL campaigns: Technique for studying electron precipitation, J. Geophys. Res. Space Physics, 120, 49224935, doi: 10.1002/2014JA020874.
6. A. J. Halford, S. L. McGregor, K. R. Murphy, R. M. Millan, M. K. Hudson, L. A. Woodger, C. A. Cattel, A. W. Breneman, I. R. Mann, W. S. Kurth, G. B. Hospodarsky, M. Gkioulidou and J. F. Fennell (2015), BARREL observations of an ICME-Shock impact with the magnetosphere and the resultant radiation belt electron loss, J. Geophys. Res. Space Physics, doi: 10.1002/2014JA020873.
7. Blum, L. W., A. Halford, R. Millan, J. W. Bonnell, J. Goldstein, M. Usanova, M. Engebretson, M. Ohnsted, G. Reeves, H. Singer, et al. (2015), Observations of coincident EMIC wave activity and duskside energetic electron precipitation on 18-19 January 2013, Geophys. Res. Lett., 42, 57275735, doi:10.1002/2015GL065245.
8. Breneman, A. W., A. Halford, R. Millan, M. McCarthy, J. Fennell, J. Sample, L. Woodger, G. Hospodarsky, J.R. Wygant, C. A. Cattell, J. Goldestein, D. Malaspina, and C.A. Kletzing (2015), Observations of a Global Coherence Scale Modulating Electron Loss Due to Plasmaspheric Hiss, Nature, 523, 193-195, doi:10.1038/nature14515
9. Halford, A. J., S. L. McGregor, M. K. Hudson, R. M. Millan, B. T. Kress (2016), BARREL observations of a Solar Energetic Electron and Solar Energetic Proton event, J. Geophys. Res. Space Physics, 121, 42054216,doi:10.1002/2016JA022462
10. Zhang, Jichun, Alexa Halford, Anthony A. Saikin, Chia-Lin Huang, Harlan E. Spence, Brian A. Larson, Geoffrey D. Reeves, Robyn M. Millan, Charles W. Smith, Roy B. Torbert, William S. Kurth, Craig A. Kletzing, Seth G. Claudepierre, J. Bernard Blake, Joseph F. Fennel, Daniel N. Baker. (2016), EMIC waves and associated relativistic electron precipitation on 25-26 January 2013, J. Geophys. Res. Space Physics, 121, 11,086-11,100, doi:10.1002/2016JA022918
11. Clilverd, M. A., C. J. Rodger, M. McCarthy, R. Millan, L. W. Blum, N. Cobbett, J. B. Brun- dell, D. Danskin, and A. J. Halford (2017), Investigating energetic electron precipitation through combining ground-based and balloon observations, J. Geophys. Res. Space Physics, 122, 534546, doi: 10.1002/2016JA022812.
12. Anderson, B. R., S. Shekhar, R. M. Millan, A. B. Crew, H. E. Spence, D. M. Klumpar, J. B. Blake, T. P. O'Brien, and D. L. Turner (2017), Spatial scale and duration of one microburst region on 13 August 2015, J. Geophys. Res. Space Physics, 122, 59495964, doi:10.1002/2016JA023752
13. Zhang, K., X. Li, Q. Schiller, D. Gerhardt, H. Zhao, and R. Millan (2017), Detailed characteristics of ra- diation belt electrons revealed by CSSWE/REPTile measurements: Geomagnetic activity response and precipitation observation, J. Geophys. Res. Space Physics, 122, 84348445, doi:10.1002/2017JA024309

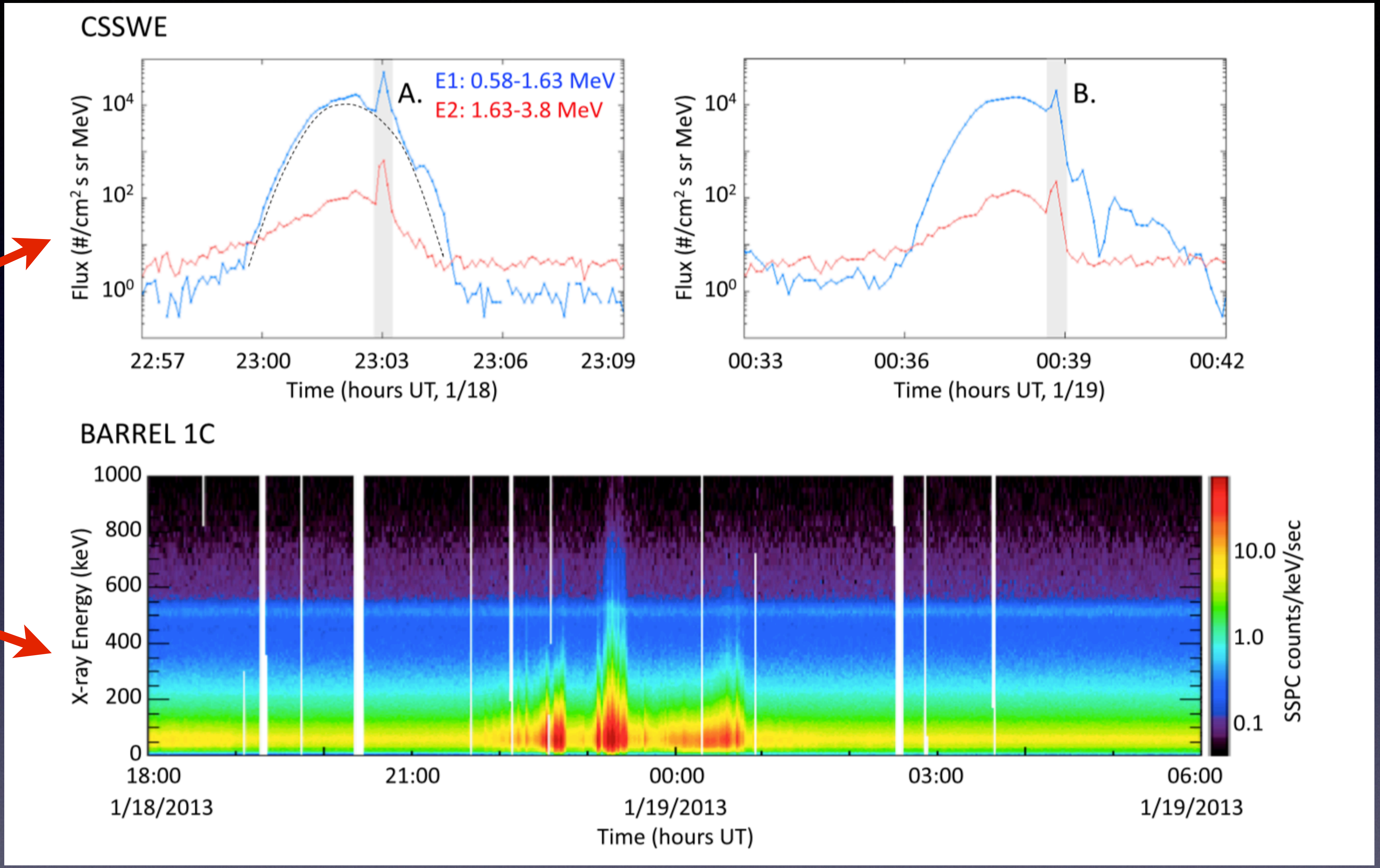
BARREL Science Objectives

- Determine electron loss rate during relativistic electron events
- Directly test models of wave-particle interactions
- Determine spatial extent and large-scale structure of precipitation.
- Determine relative importance of different types of precipitation

Electron Loss Rate

CSSWE 0.5-3.8 MeV electrons

BARREL X-ray Observations



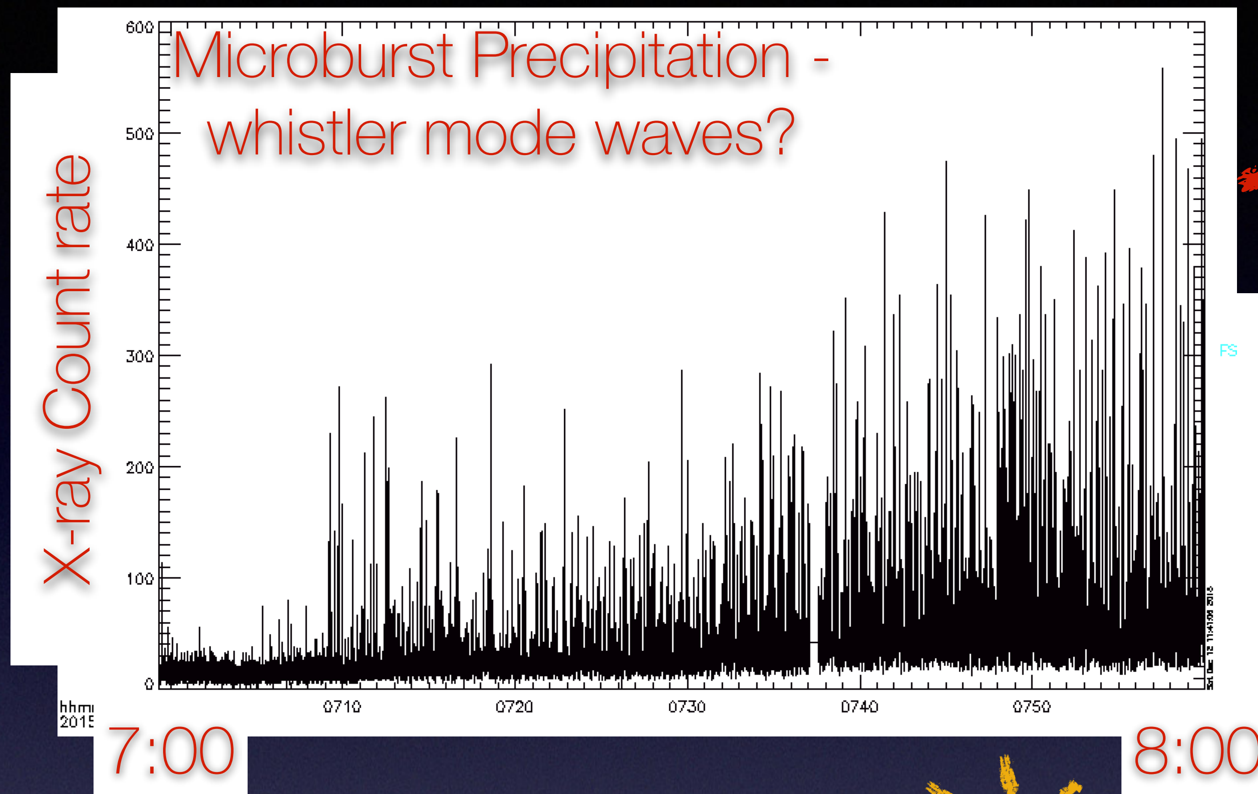
Blum et al., 2013 (GRL)

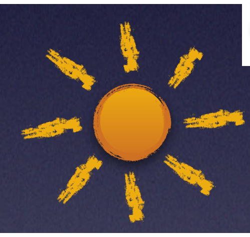
- ~5-7% of the total electron content in L= 3.5–6 lost for 0.58–1.63 MeV *[Blum et al., 2013; Zhang et al., 2016]*
- ~20 such events could empty the entire outer belt.

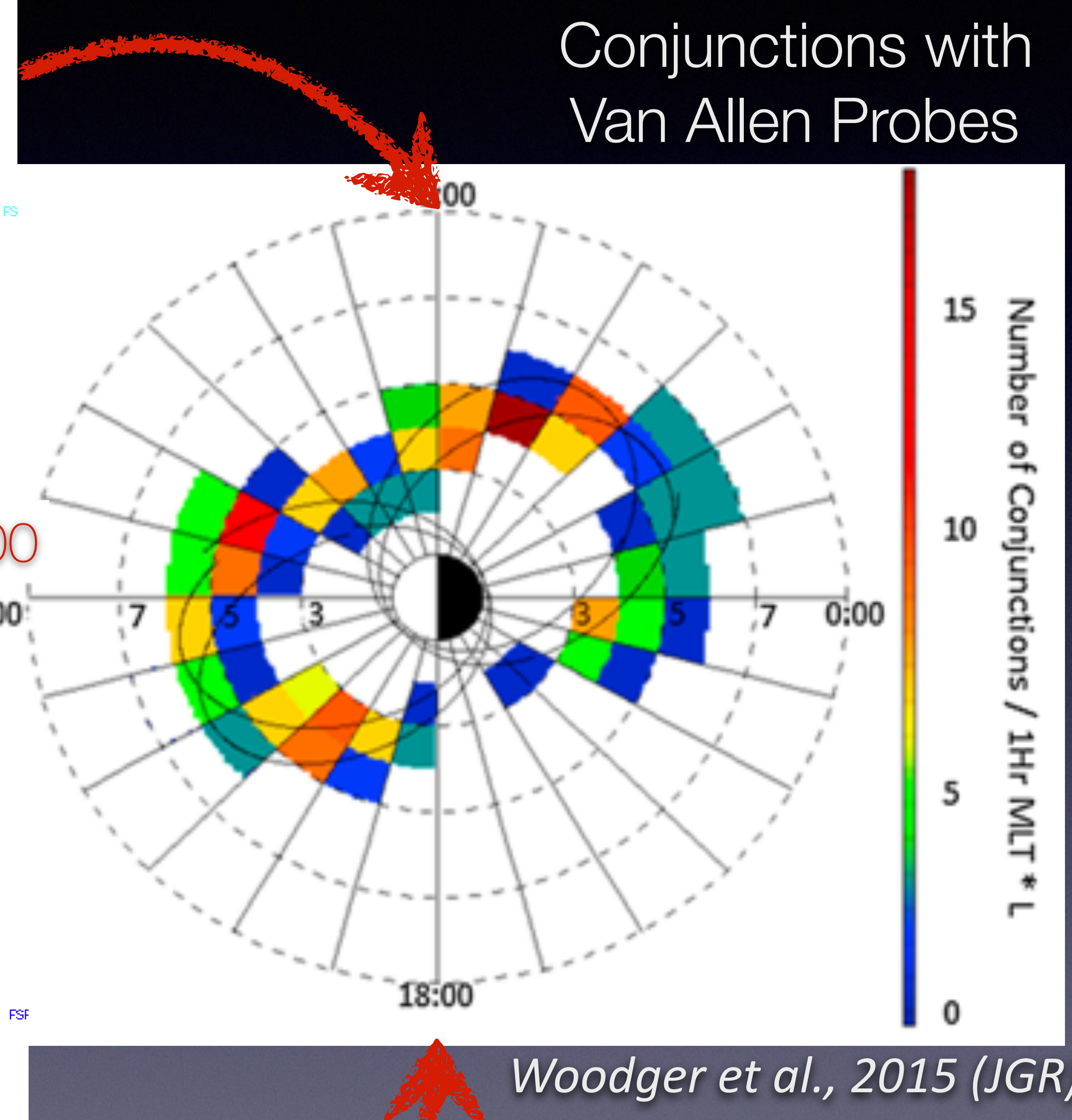
BARREL Science Objectives

- Determine electron loss rate during relativistic electron events
- Directly test models of wave-particle interactions
- Determine spatial extent and large-scale structure of precipitation.
- Determine relative importance of different types of precipitation

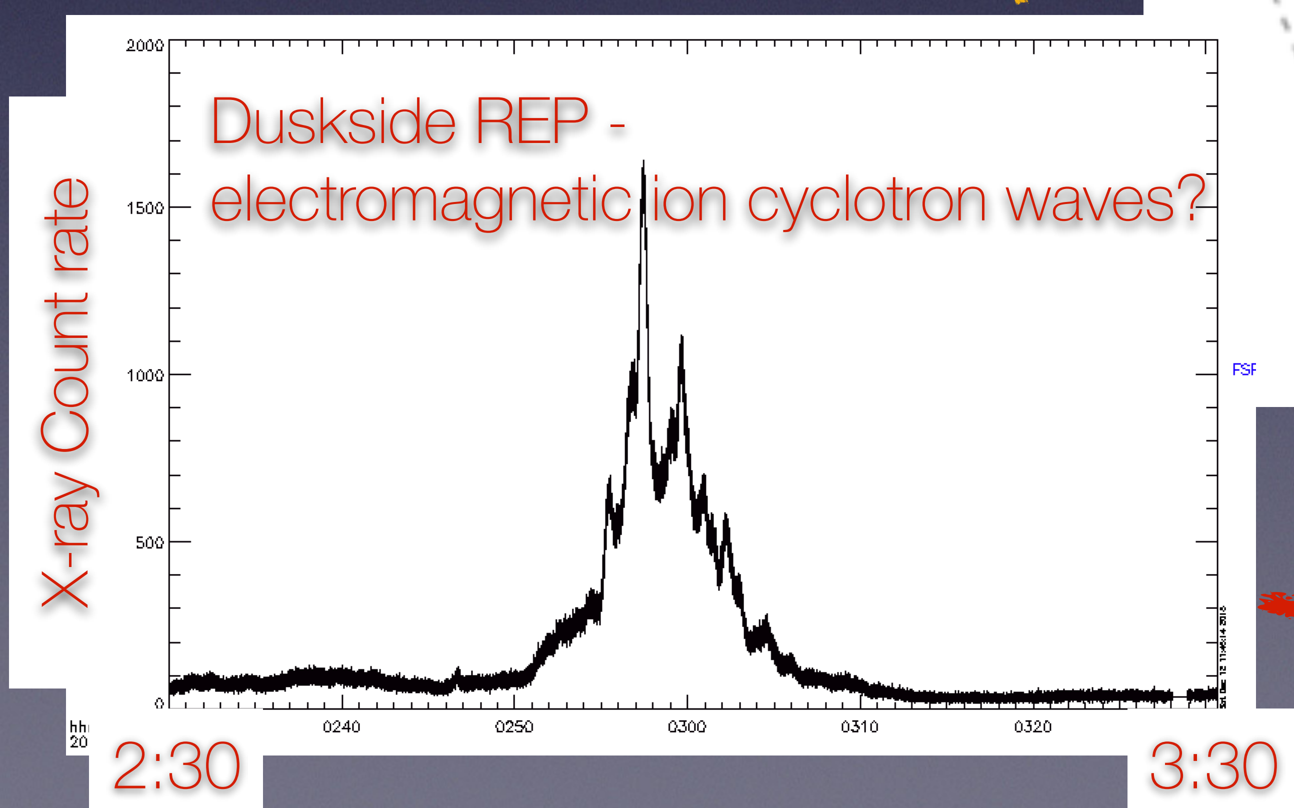
Test Wave-Particle Interaction Models





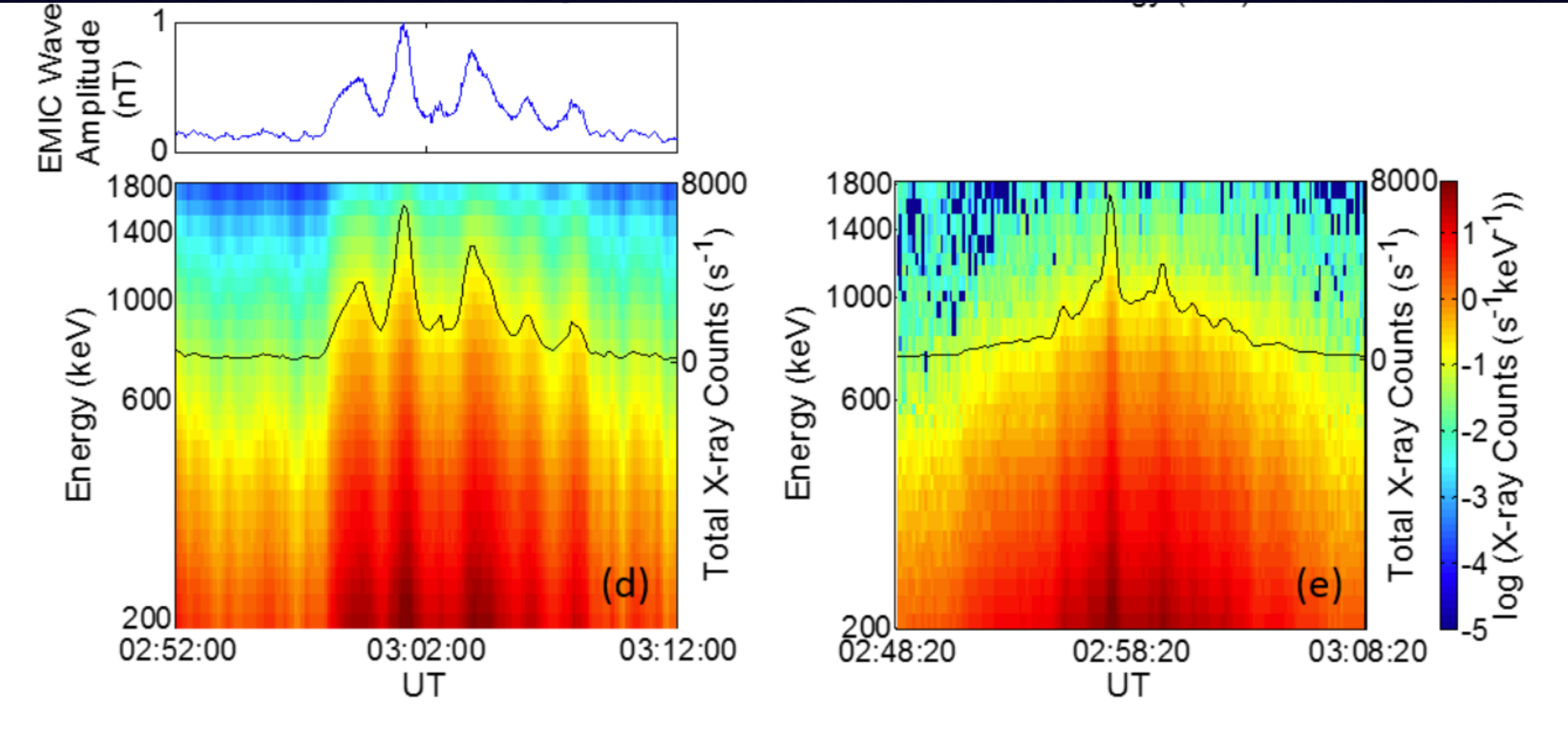


Woodger et al., 2015 (JGR)



Quantitative Test of EMIC Scattering

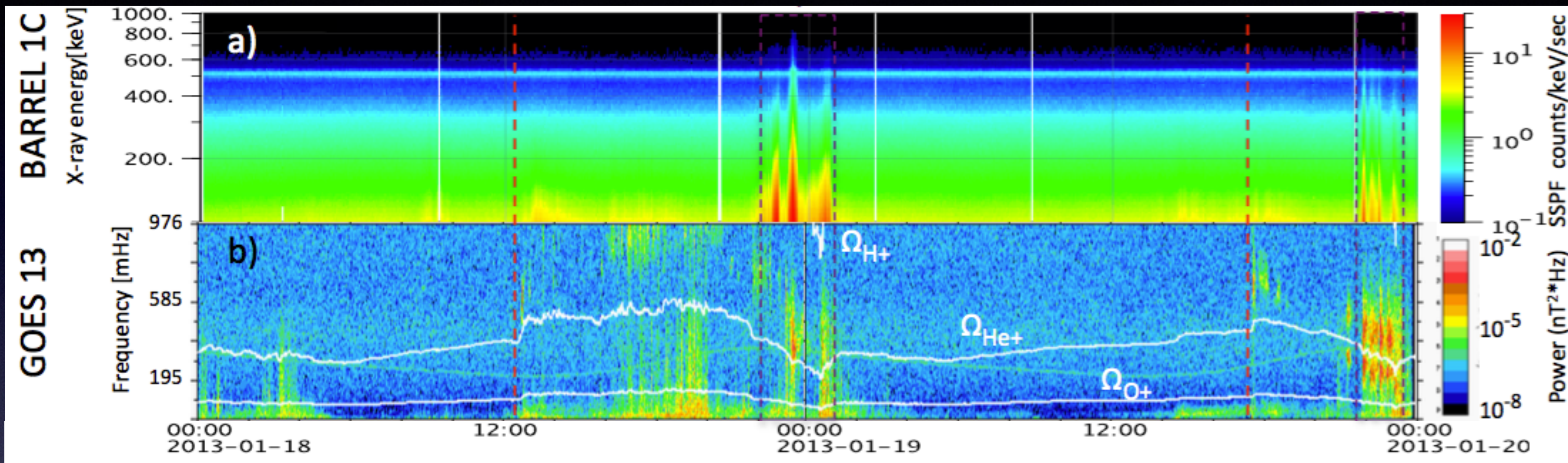
- Quasi-linear diffusion model to simulate wave-particle interaction
  - GOES wave parameters
  - plasma and energetic particle parameters from Van Allen
- Model X-rays using electron distribution from model



Li et al., 2014 GRL

- J. Zhang et al., 2016 (JGR) examined a different case study

EMIC Wave REP Correlation



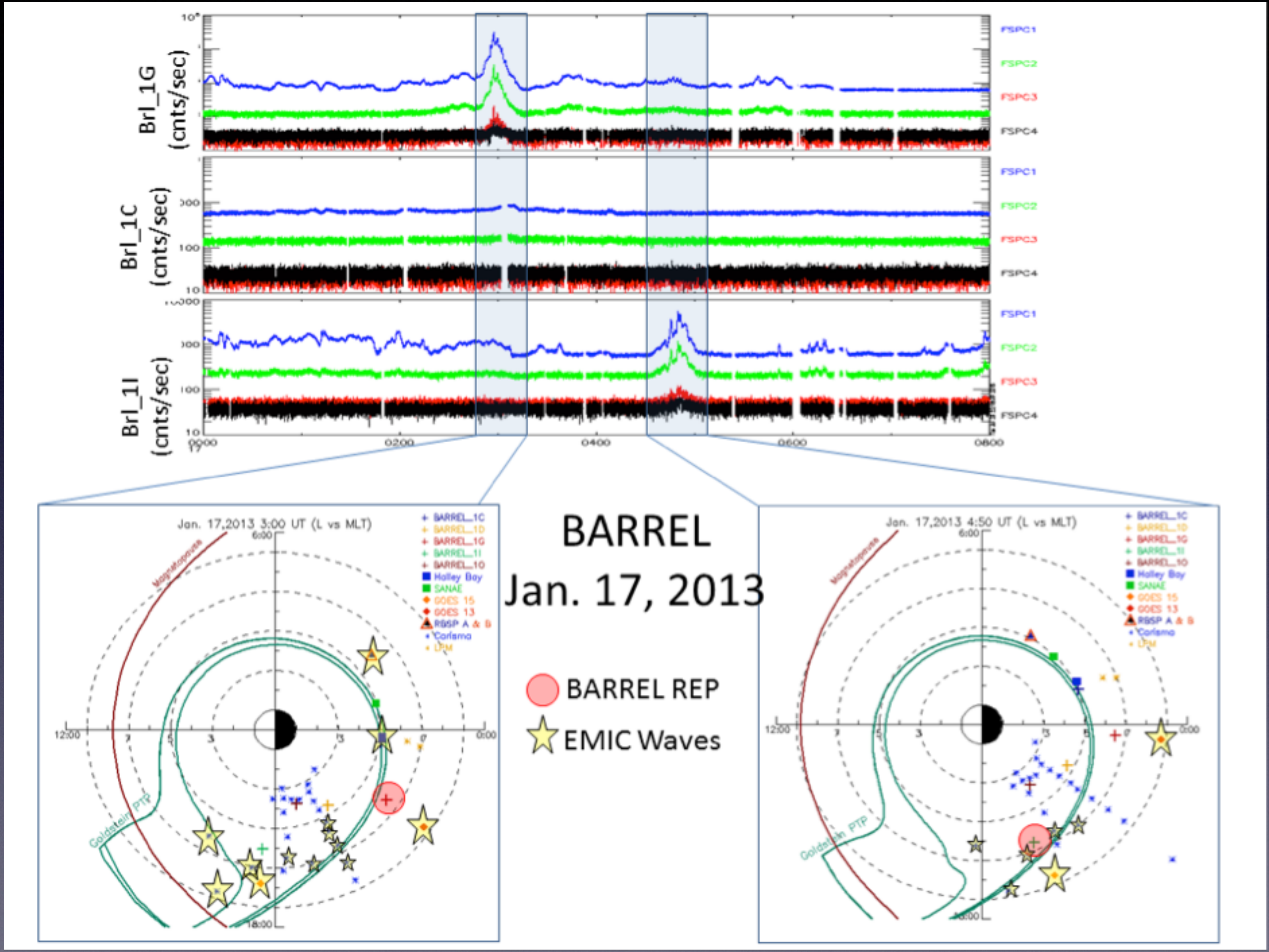
Blum et al., 2015 (GRL)

- Correlation between EMIC waves and duskside relativistic electron precipitation observed
- However: waves are wide-spread, but precipitation is localized

BARREL Science Objectives

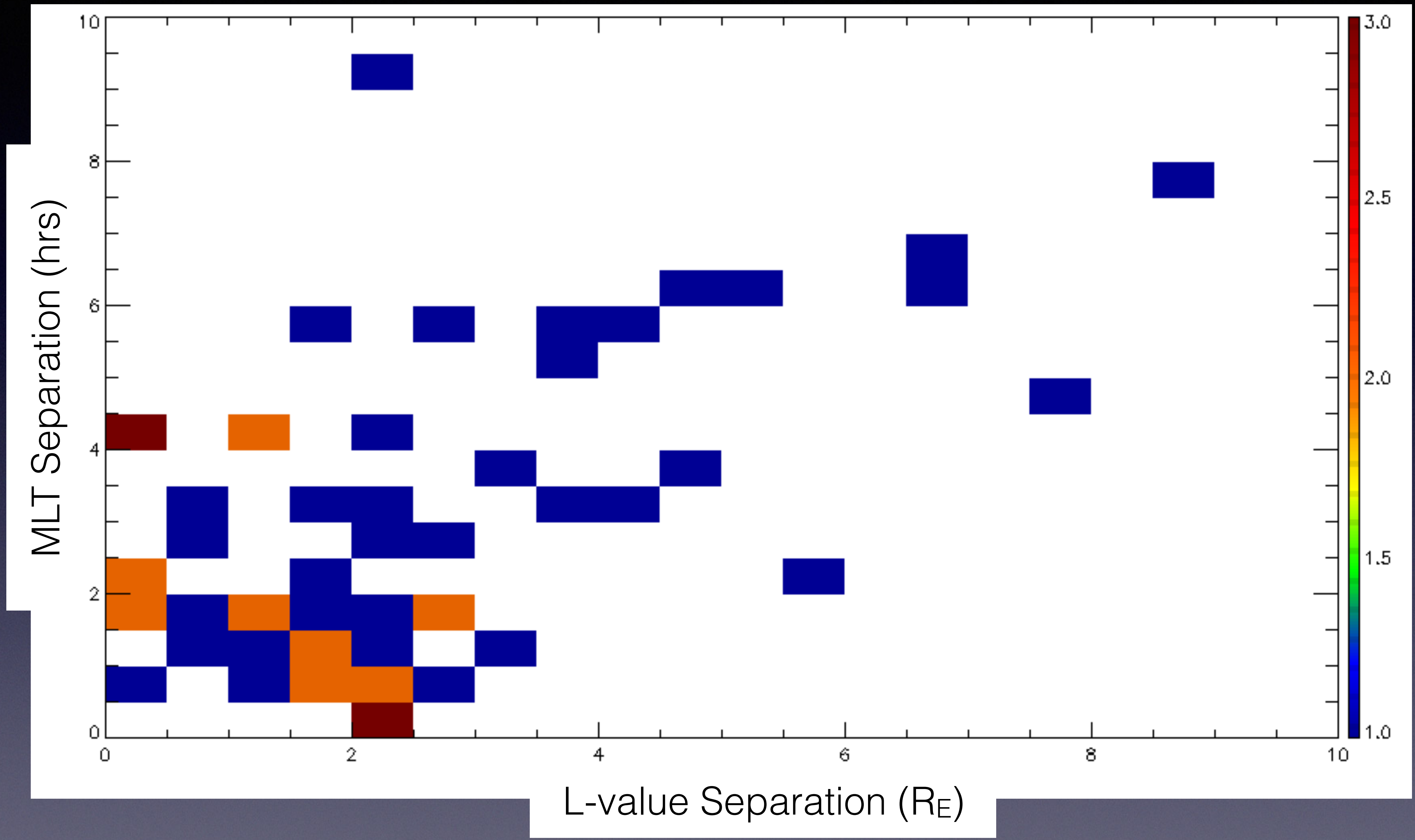
- Determine electron loss rate during relativistic electron events
- Directly test models of wave-particle interactions
- Determine spatial extent and large-scale structure of precipitation.
- Determine relative importance of different types of precipitation

Duskside Precipitation is Highly Localized



Woodger et al., submitted to JGR

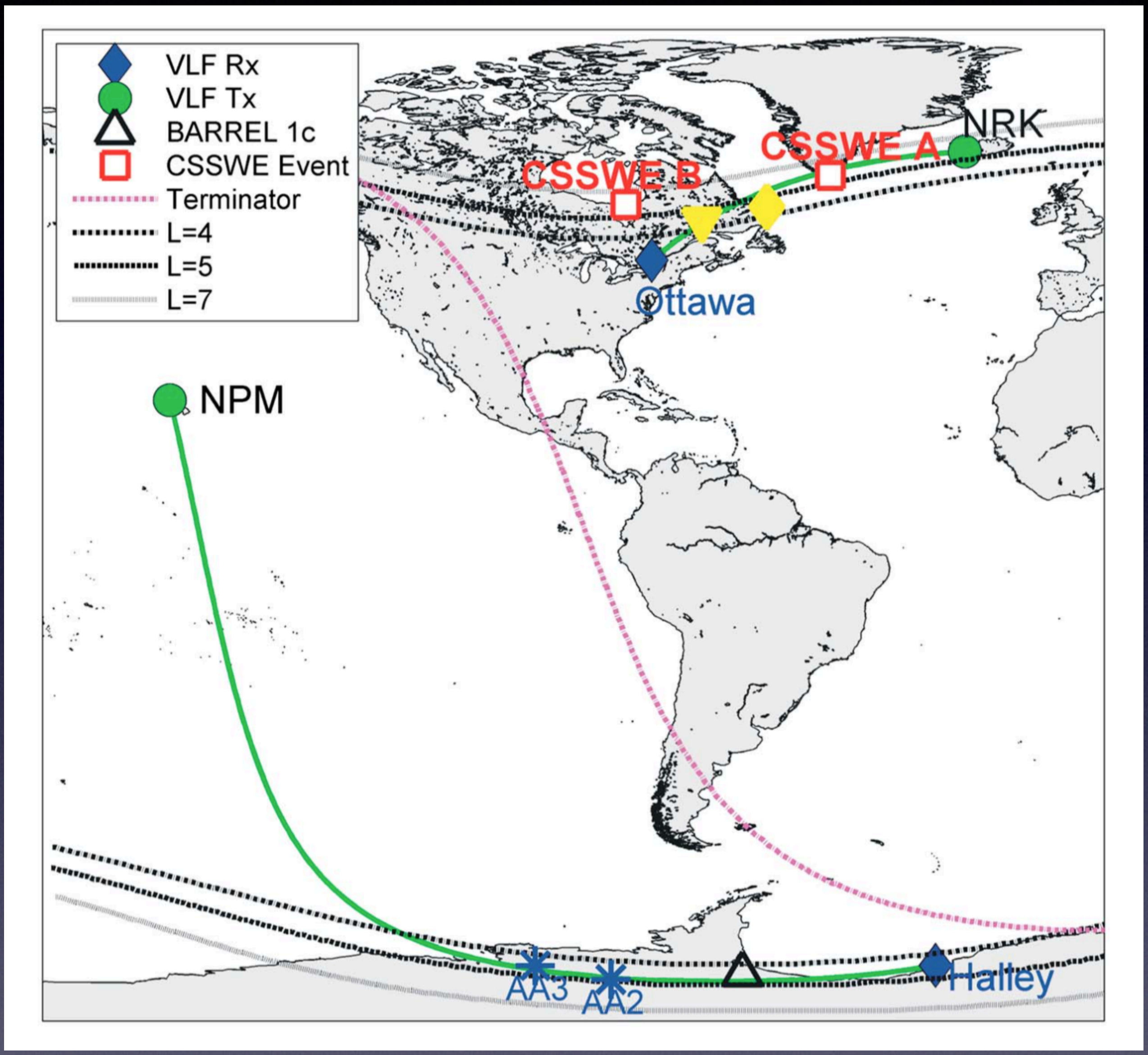
Spatial Scale of Duskside Precipitation



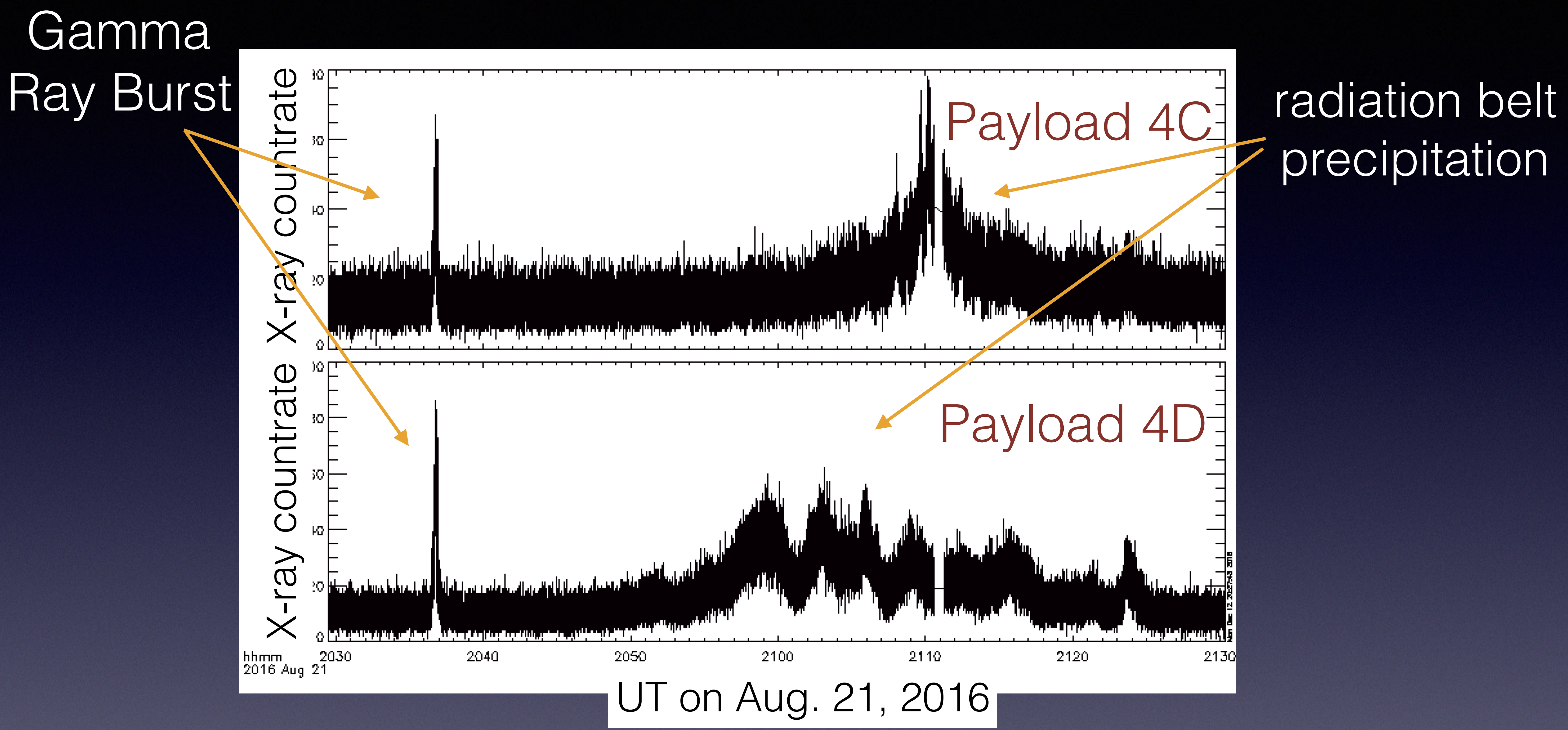
- During BARREL Antarctic campaigns, 18 dusk-side relativistic electron precipitation events were detected.
- In all cases, only single balloon detected the event

Spatial Structure and Evolution of Precipitation

- Case study by Clilverd et al., (2017) combined data from BARREL, CSSWE, riometers and AARDDVARK
- Two duskside patches exhibit different dimensions, with the first event covering ~18–26° in longitude and the second 50–70° (1.5–3.5 h in MLT).
- Found precipitation patches drifting westward at speeds that are consistent with 10–1000 keV ion drift periods of 5–11 h at L ~ 5.

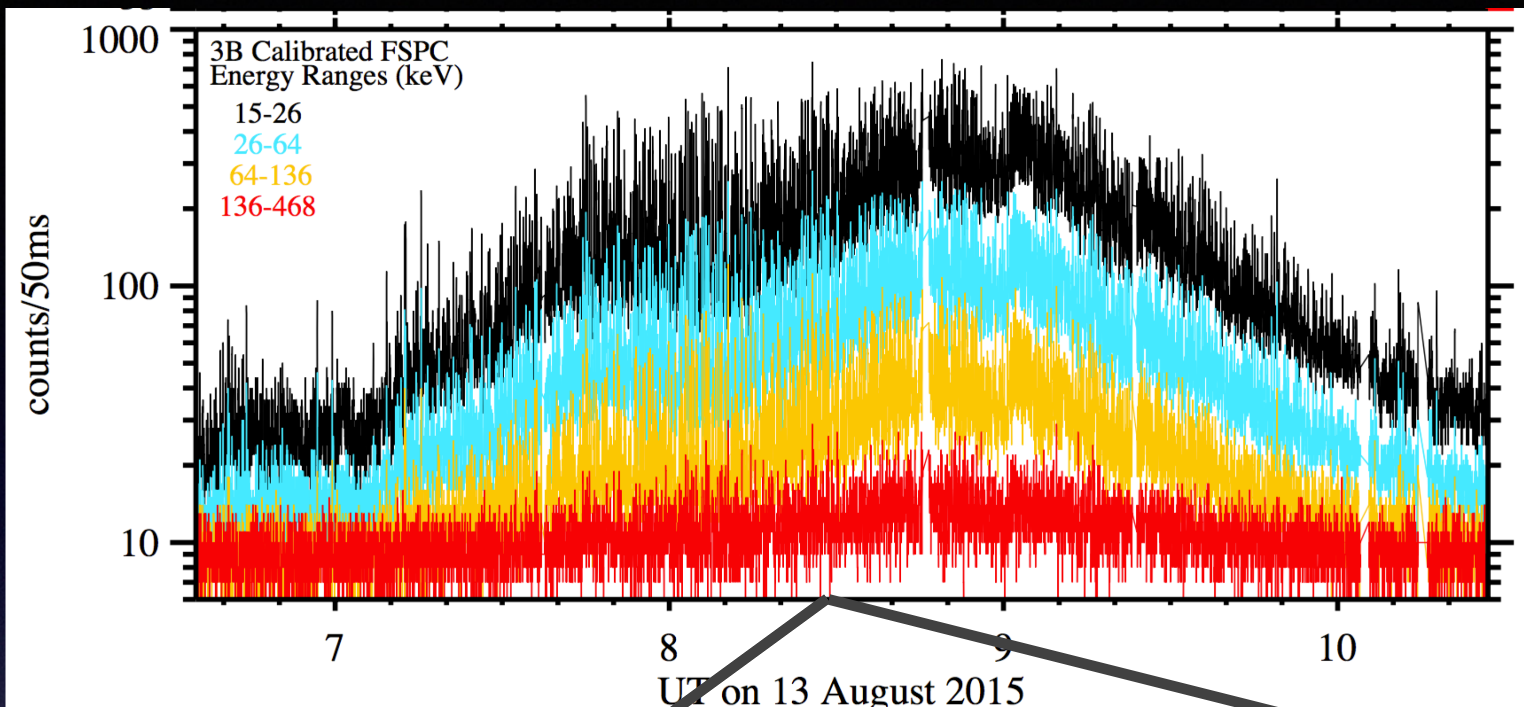


Small-scale Structure of Relativistic Precipitation

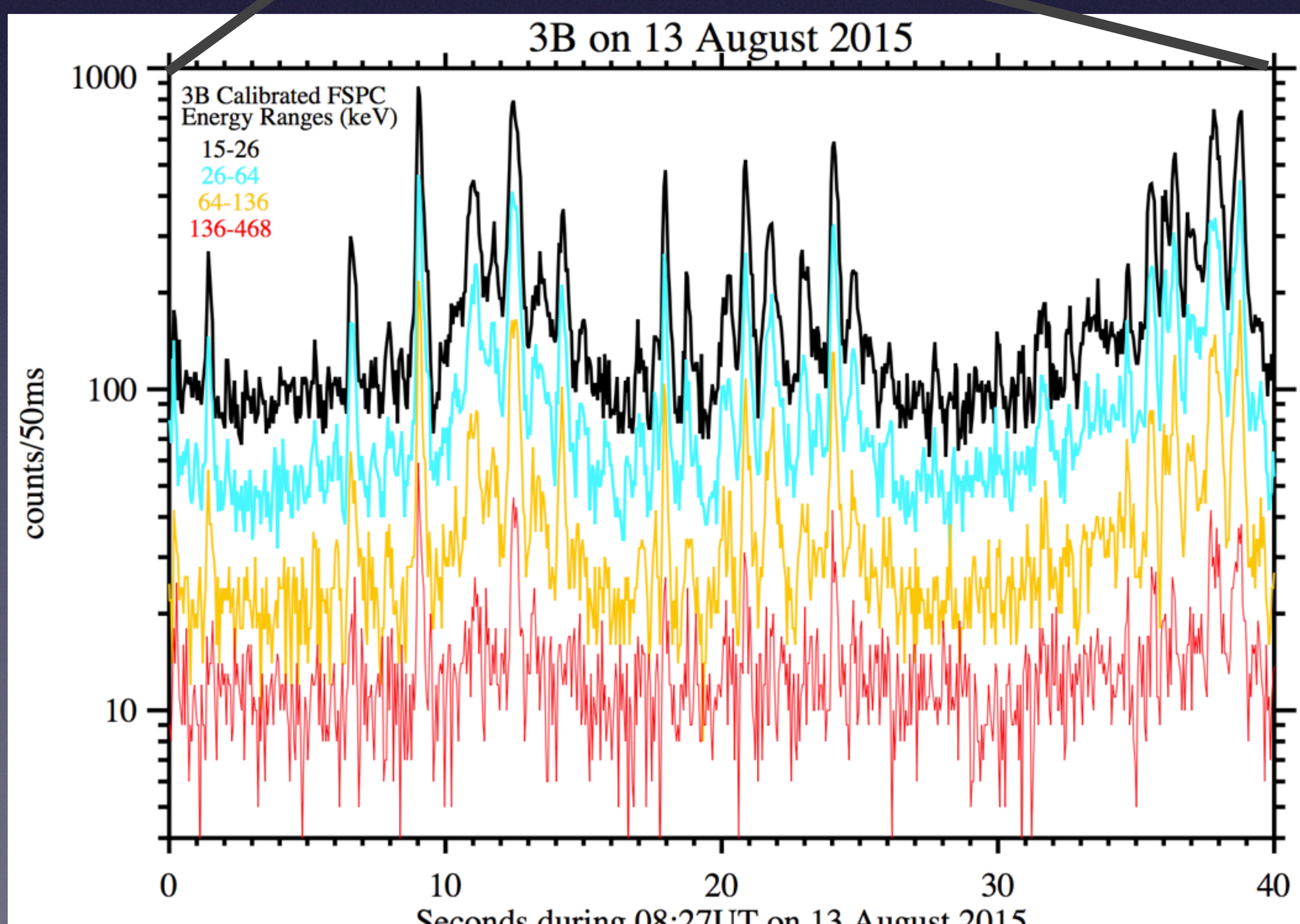


- During Sweden 2015 campaign, two balloons detected duskside REP
- Balloons were ~100 km apart, of order the field of view of each payload
- Differences imply structure at <~100 km scales (~1000 km at equator)

BARREL Microburst Observations



- Microbursts observed for ~4 hours (0635-1027 UT)
- Balloon at fixed L~5.6-5.8, drifts 4 hrs of MLT
- Bursts are superposed on more slowly varying precipitation

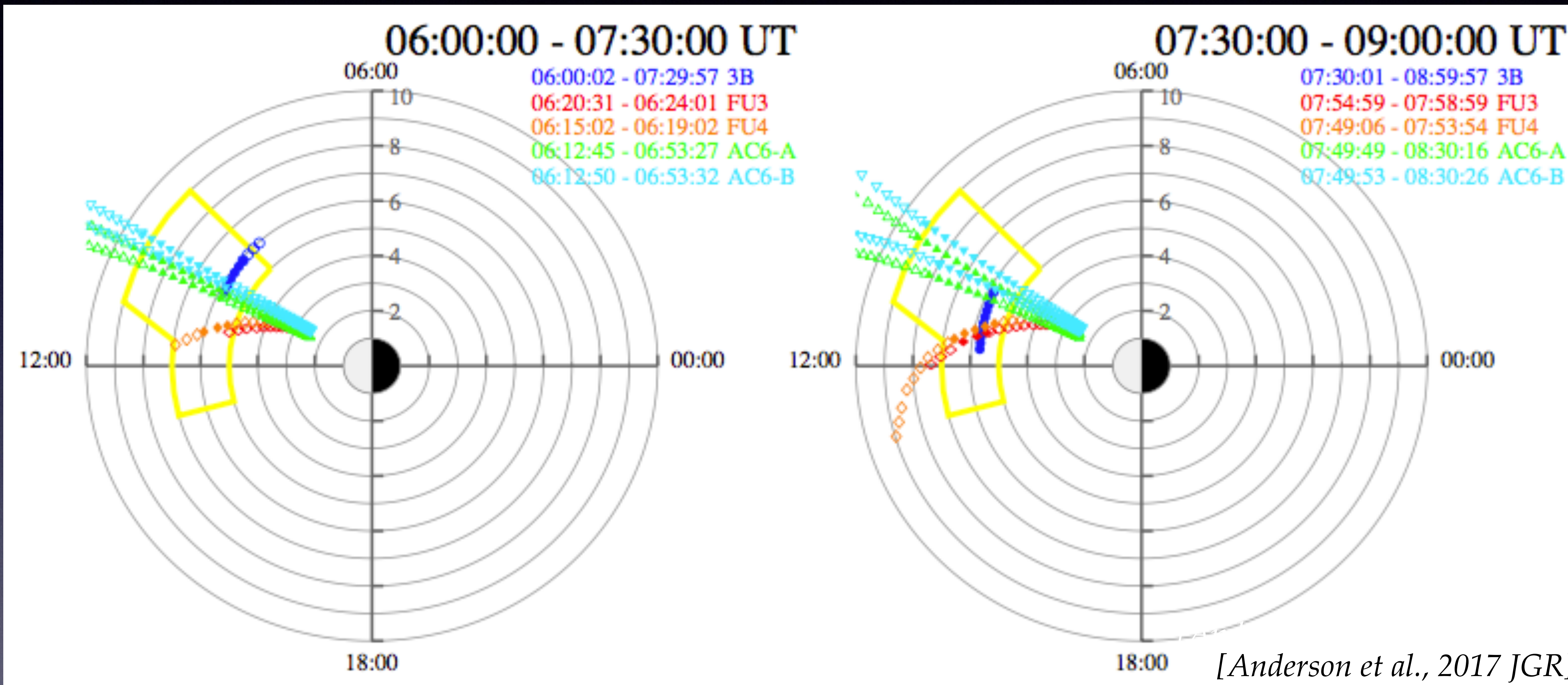


- ~200 msec long bursts are concentrated in "trains" 5-10 seconds long

[Anderson et al., 2017 JGR]

Spatial Extent of Microburst Region

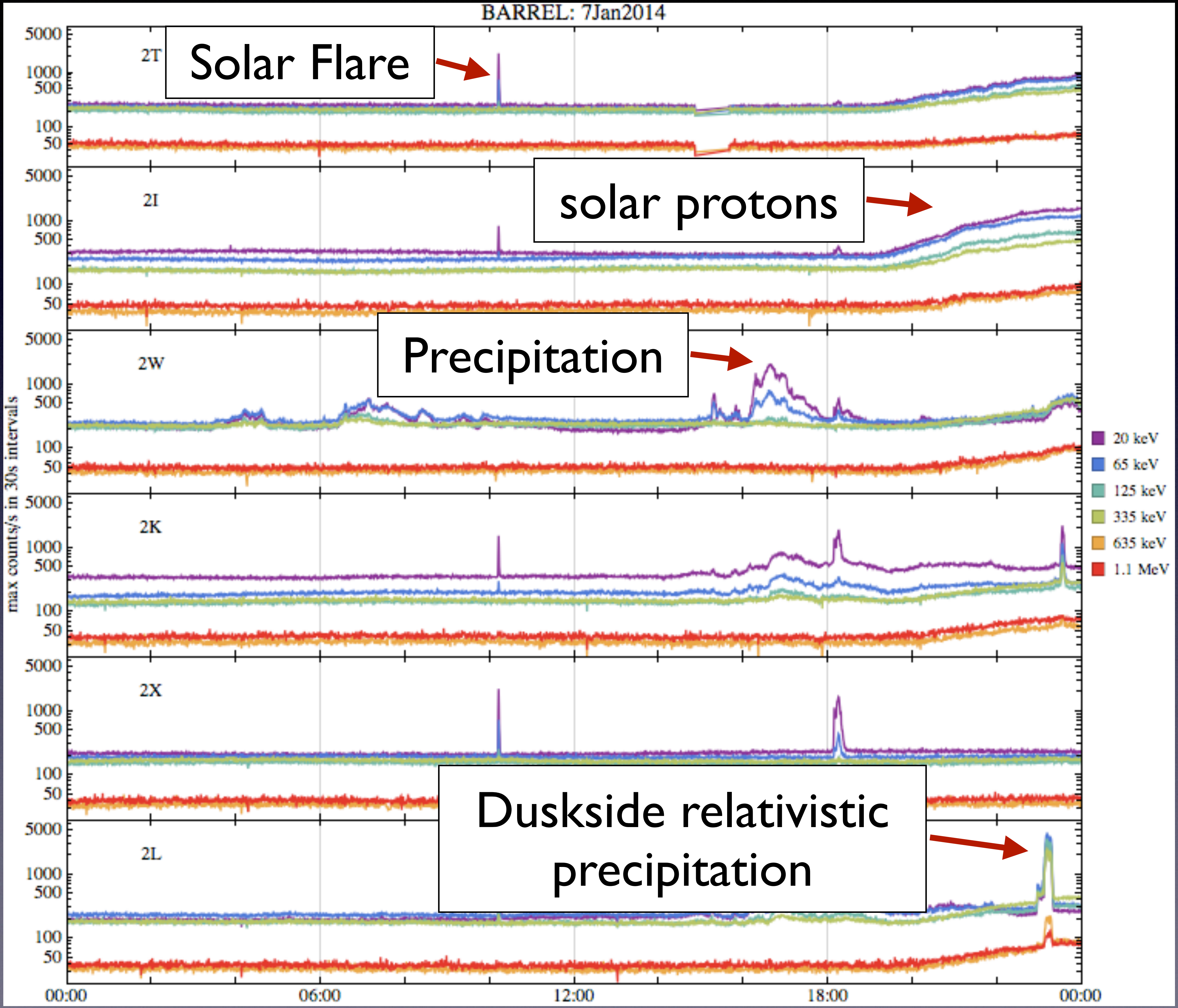
- Anderson et al., (2017) combined data from BARREL, FIREBIRD II, and AC-6 to quantify the spatial scale



[Anderson et al., 2017 JGR]

- Persistent microbursts observed for ~9 hours
- Precipitation extends over large region L~5-10 and 0900-1300 MLT
- Microburst region appears to move outward in time

BARREL Observes all X-rays



SEPs: Probing the Open-Closed Boundary

- Halford et al., (2016) used atmospheric gamma ray lines produced by SEPs to map the open-closed boundary.
- Six BARREL payloads were aloft, spanning all MLT sectors and L values.
  - Three payloads were in a tight array (~2 h in MLT and ~2 ΔL) inside the inner magnetosphere
  - Three payloads mapped to higher L values with one payload on open field lines for the entire event, and the others crossing from open to closed field lines

Conclusions

- Now well-established that EMIC waves cause relativistic electron precipitation
  - Quasi-linear theory can reproduce observations
- EMIC-driven duskside precipitation is highly localized
  - region is smaller than 0.5 in L and 1-2 hours of MLT even when EMIC waves are observed across the magnetosphere.
  - Precipitation is structured at small scales (~100 km at the ionosphere)
- Microburst precipitation lasts for many hours and can extend over a large spatial region (~4 hours MLT, L~5-10)