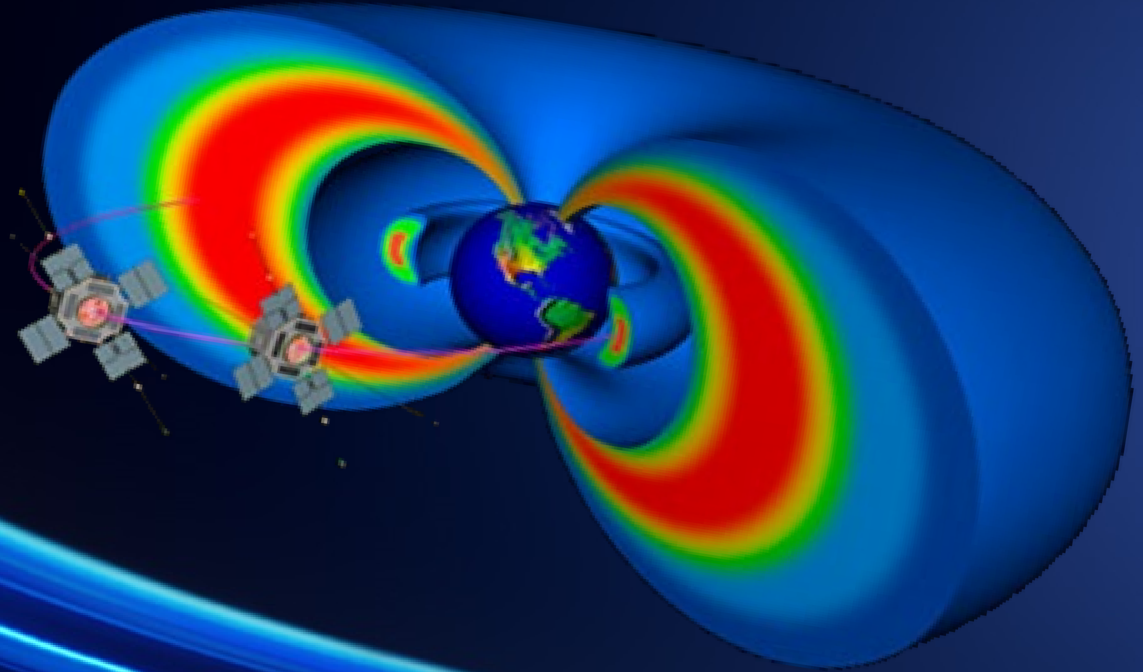
Precipitation of Energetic Particles from the Inner Magnetosphere



Weichao Tu

West Virginia University

2020/07/27

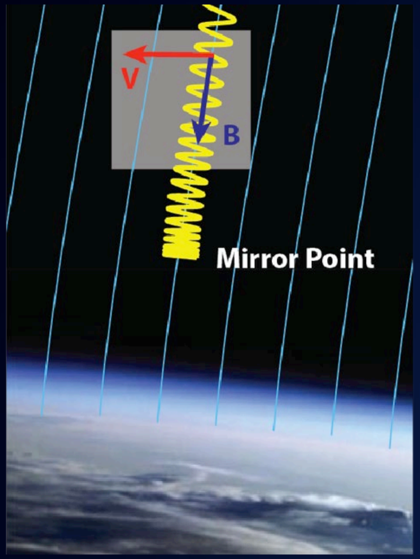
This presentation is being recorded

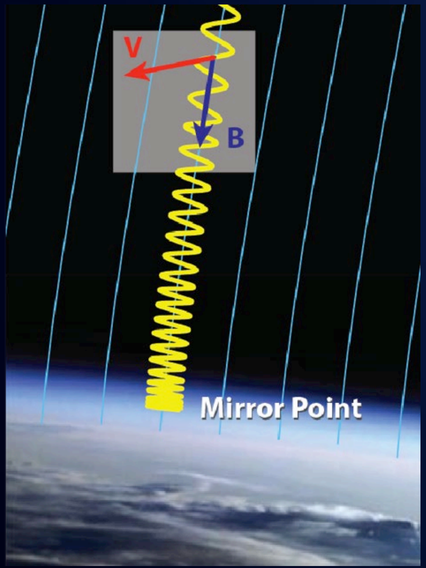
Outline

- What are we talking about?
- Why do we care?
- What drives precipitation?
- Characterizing precipitation: observations
- Characterizing precipitation: modeling
- Unsolved questions and future opportunities

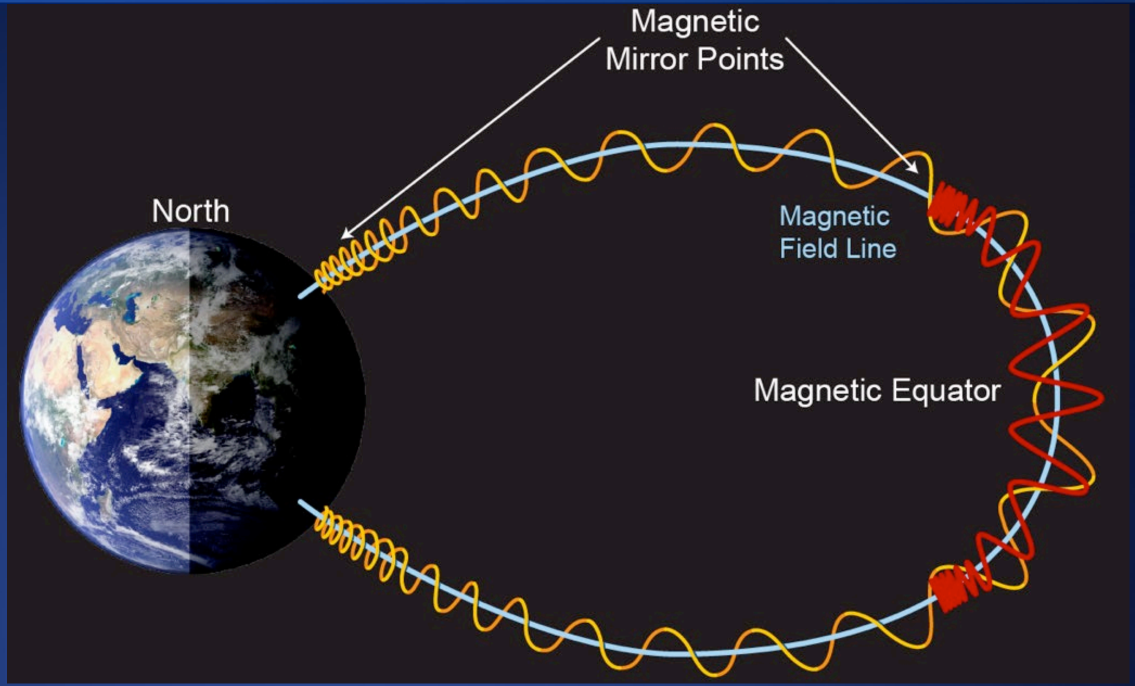
This type of precipitation?

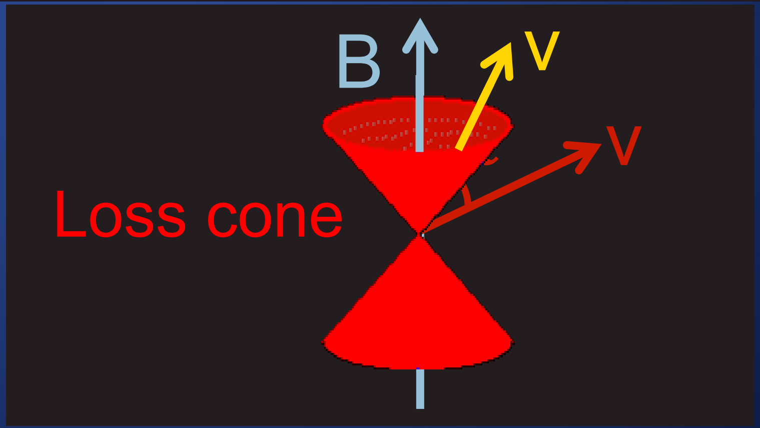
What are we talking about?





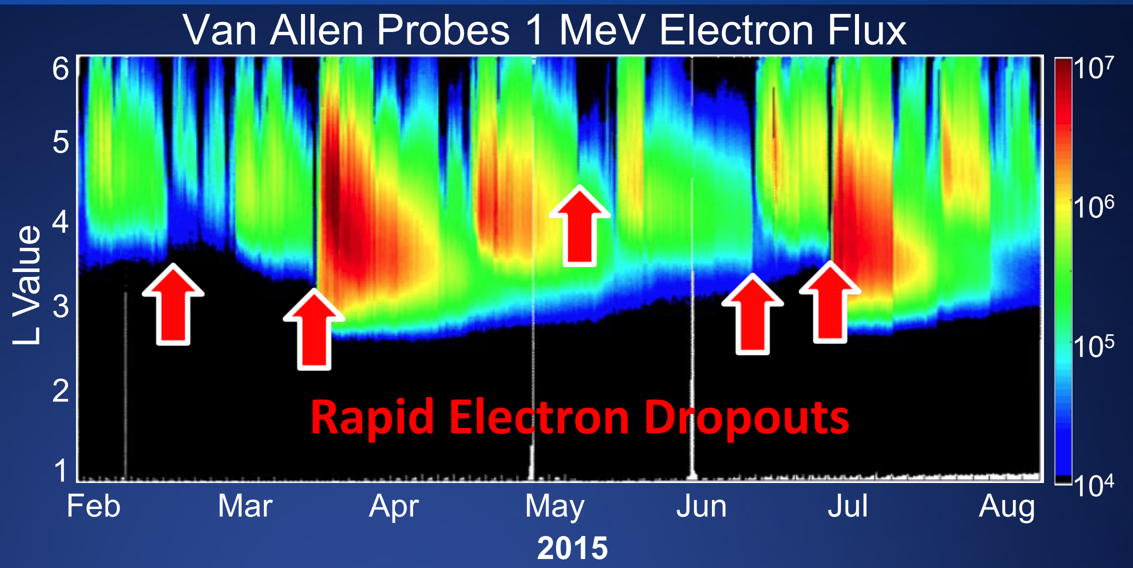
- Pitch angle outside loss cone: trapped
- Pitch angle inside loss cone: precipitation

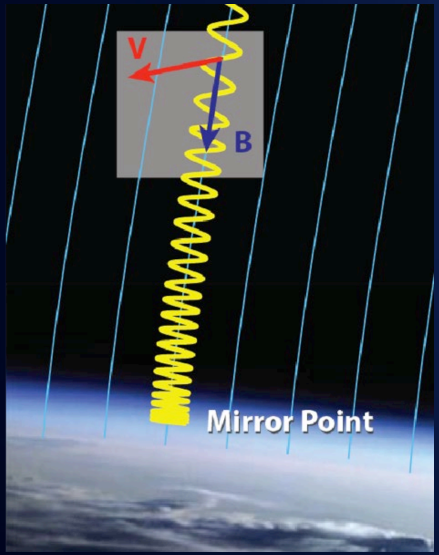




Why do we care?

1. Precipitation is one of the main loss mechanisms of radiation belt (electrons: 100s keV-multiple MeV; protons: 10s-100s MeV) and ring current particles (10s-100s keV).

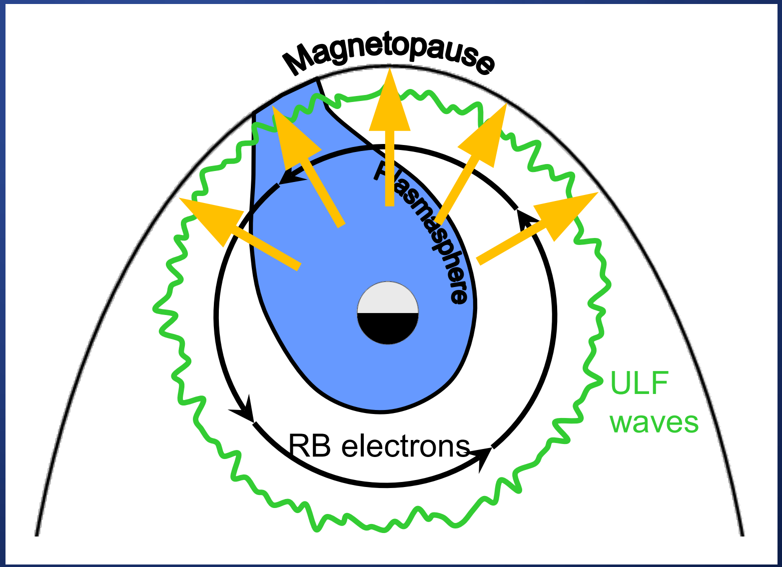




Precipitation

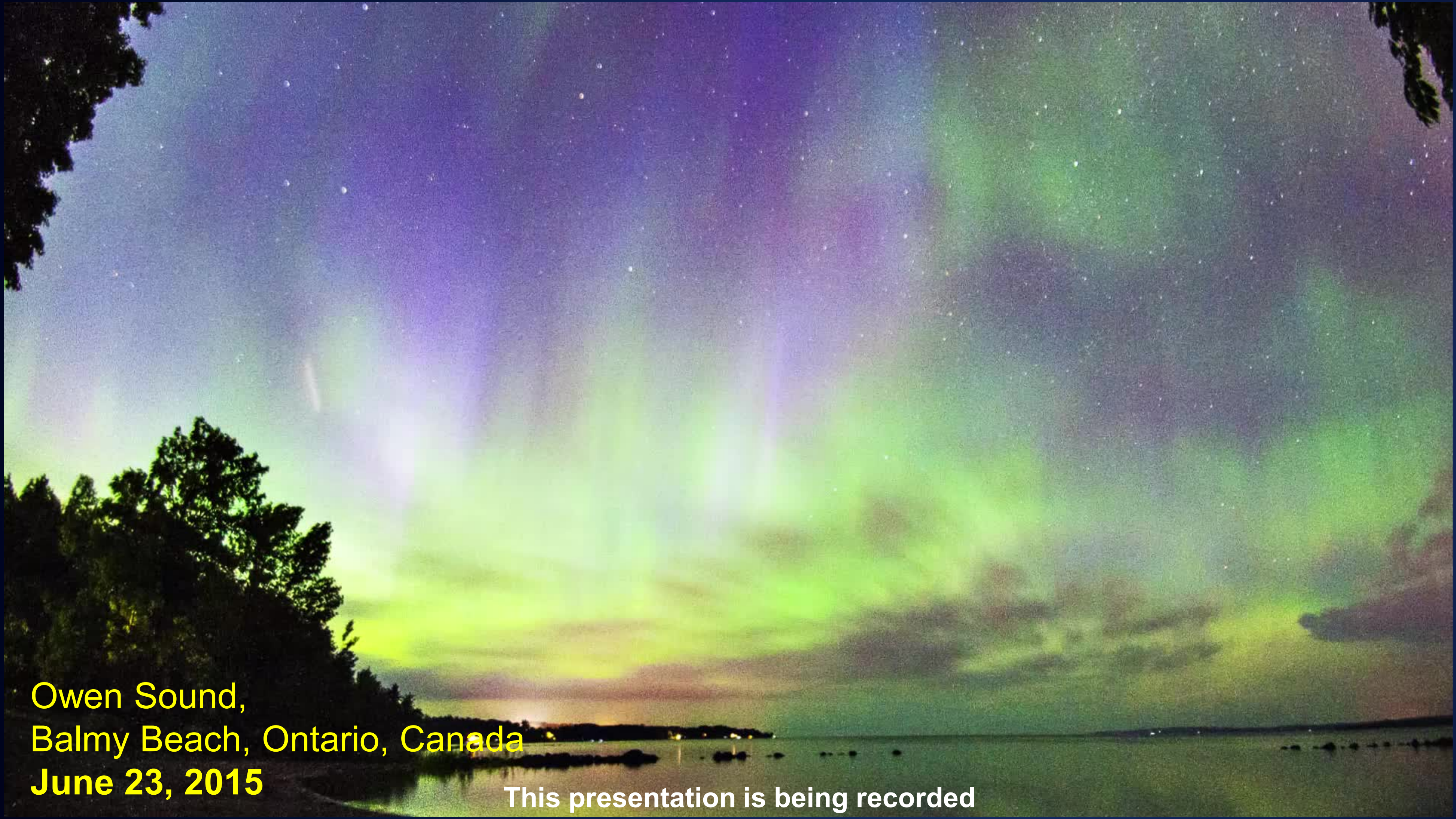
vs.

Magnetopause shadowing



Why do we care?

2. Precipitation (0.1-10s keV) produces spectacular aurora.



Owen Sound,
Balmy Beach, Ontario, Canada
June 23, 2015

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Why do we care?

2. Precipitation (0.1-10s keV) produces spectacular aurora.

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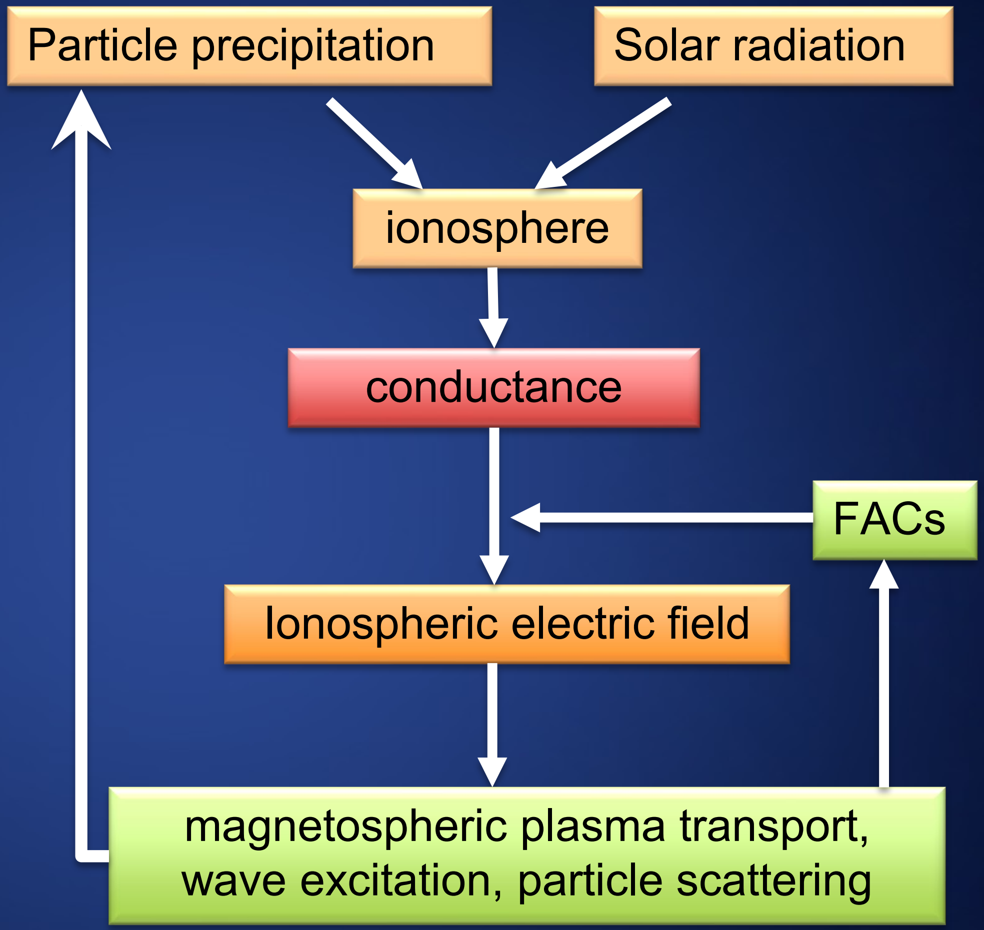
Why do we care?

3. Precipitation of auroral particles is an important component of M-I coupling.

- Precipitating particles directly impact ionospheric conductance [e.g., Robinson+ 1987; Newell+ 2009].
- Conductance is a critical parameter of ionospheric electrodynamics, which will in turn feed back to magnetospheric precipitation [e.g., Raeder+ 1996; Yu+ 2016].



[Courtesy of Y. Yu]

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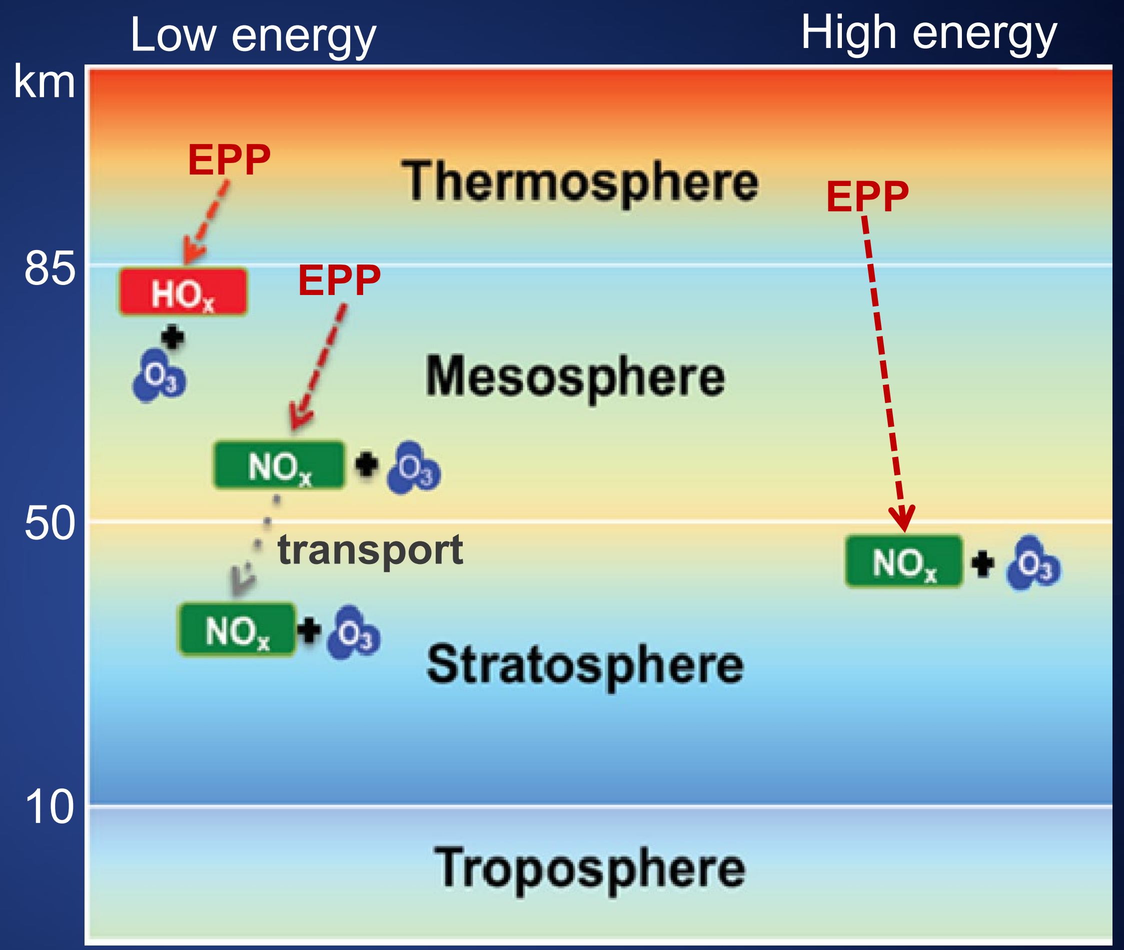
Why do we care?

4. Precipitation of auroral to relativistic particles has a strong impact on atmospheric chemistry.
    - Energetic particle precipitation (EPP) could produce NO_x and HO_x in the upper and middle atmosphere, which are powerful ozone destroyers [e.g., Randall+ 2005; Turunen+ 2009; Rozanov+ 2012; Andersson+ 2014; Seppala+ 2015]



(Modified from Seppala+ [2014])

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- What are we talking about?
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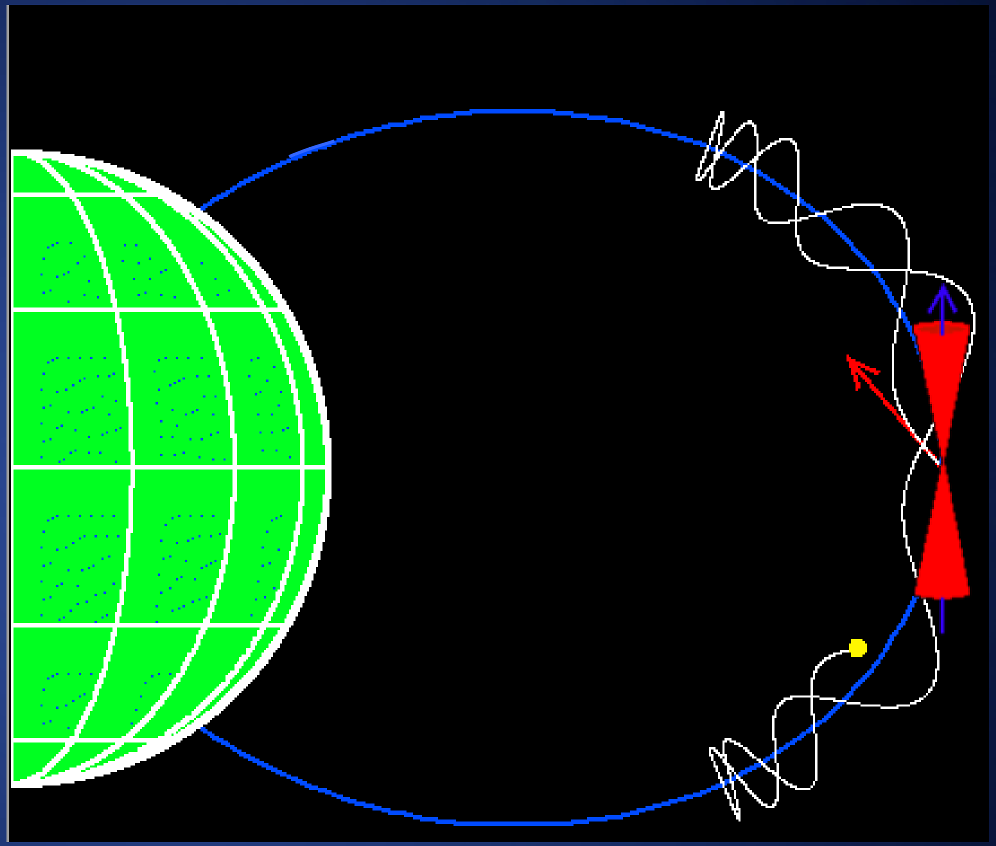
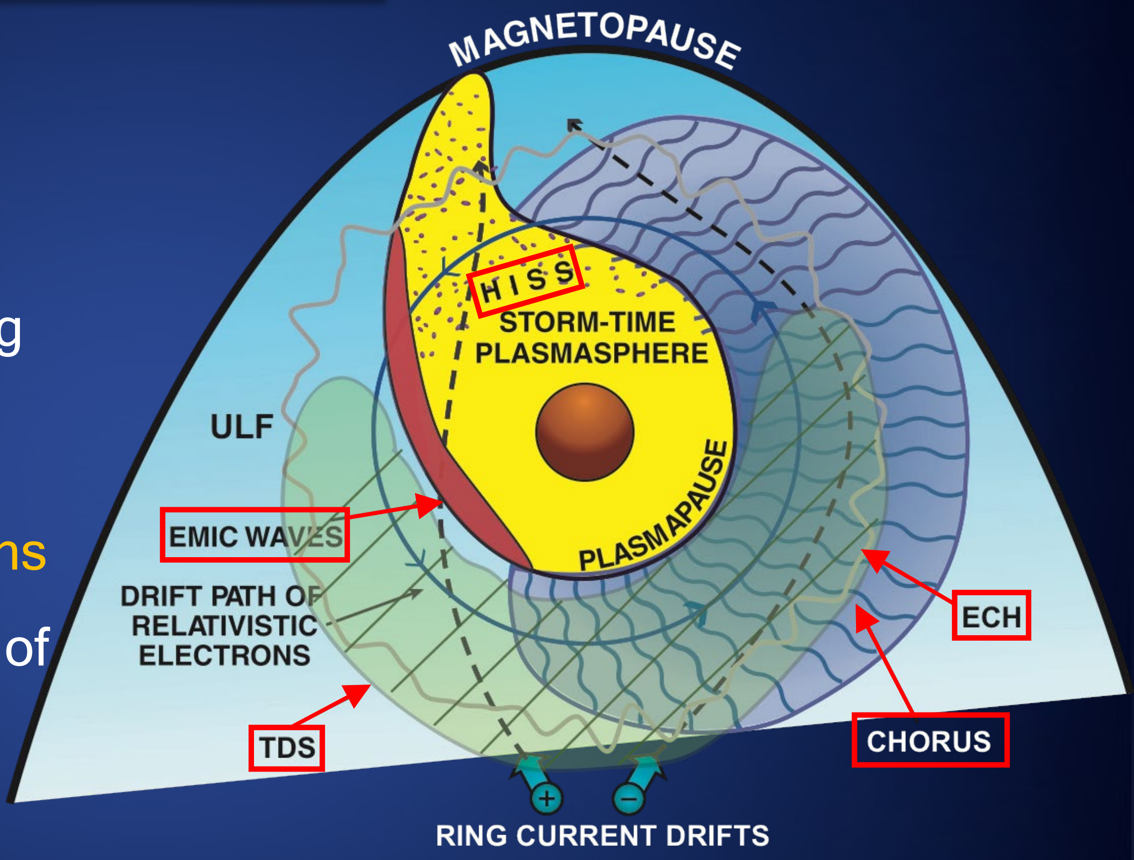
What drives precipitation?

- Pitch angle scattering into the loss cone
  - Violate 1st or 2nd adiabatic invariant
  - Wave-particle interactions: EMIC, chorus, hiss, ECH,…
  - Anomalous magnetic field geometries: field line curvature scattering, drift orbit bifurcation
- Enlarged loss cone
  - Inward radial transport driven by ULF waves
  - 1st and 2nd invariants are conserved



Pitch angle scattering by waves

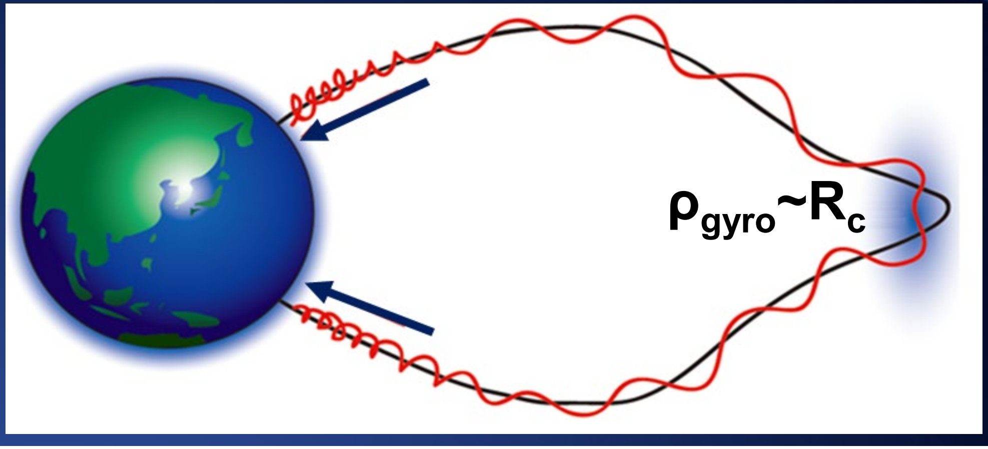
- Gyroresonance (violate the 1st invariant): $$\omega - k_{//} v_{//} = n|\Omega| / \gamma$$
- Population of waves:
  - Chorus: outside plasmapause, premidnight to afternoon, scattering 1s-10s keV electrons
  - ECH (electrostatic electron cyclotron harmonic): outside plasmapause, premidnight to dawn, scattering 100 eV to a few keV electrons
  - Plasmaspheric hiss: inside plasmasphere or plumes, stronger on dayside, scattering 10s-100s keV electrons
  - EMIC (electromagnetic ion cyclotron): overlap region of ring current and plasmasphere, scatter 10-100 keV proton and > MeV electrons
  - TDS (Time domain structures): dusk to dawn, scatter <10s keV electrons

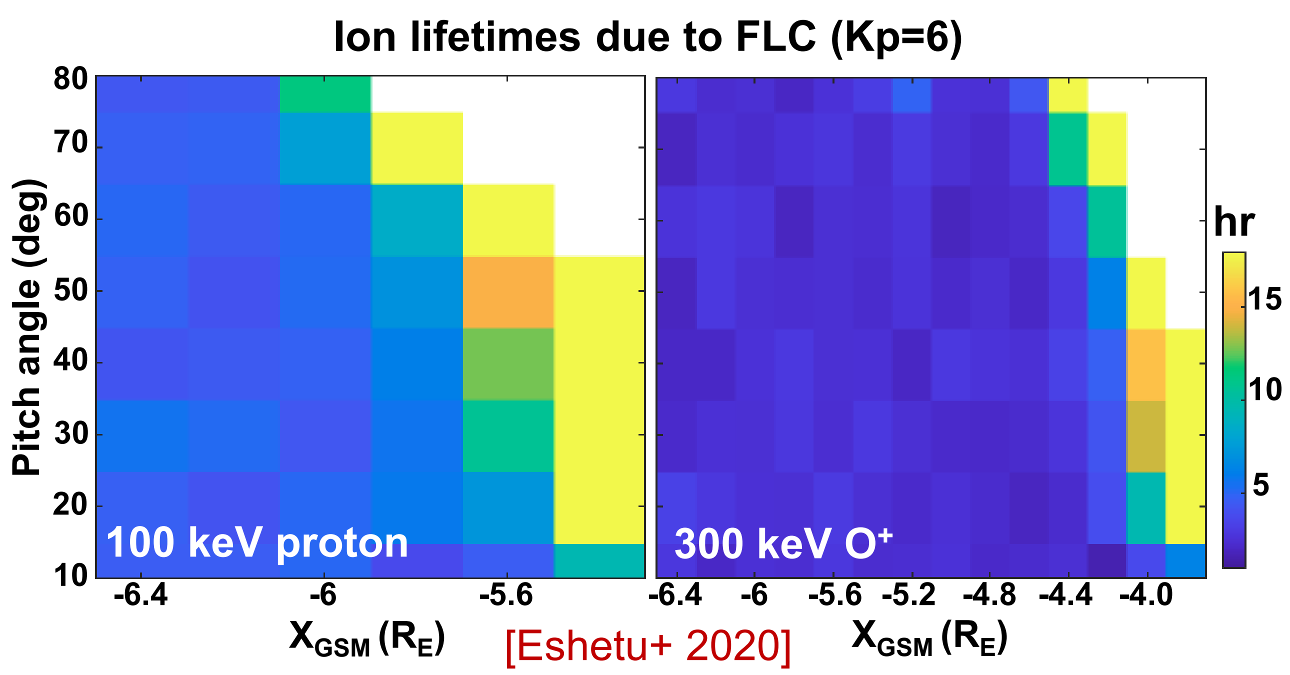


[W. Li, 2019 GEM tutorial]

Pitch angle scattering by FLC

- Field Line Curvature (FLC) Scattering:
  - occurs when the magnetic field lines are highly stretched: gyroradius of the particle is comparable to the radius of curvature of the field line
  - mostly on the nightside at equator
- Violate the 1st adiabatic invariant, leading to pitch angle scattering
- More significant for higher energy particles at larger L, scattering:
  - Plasma sheet: keV electrons and protons [e.g., Büchner&Zelenyi 1989, Eshetu+ 2018]
  - Ring current: 100s keV protons at L>5, 100s keV O^+ at L>4 [e.g., Eshetu+ 2020]
  - Radiation belts: >10s MeV protons in inner belt [e.g., Tu+ 2014], MeV electrons in outer belt [e.g., Artemyev+ 2015]





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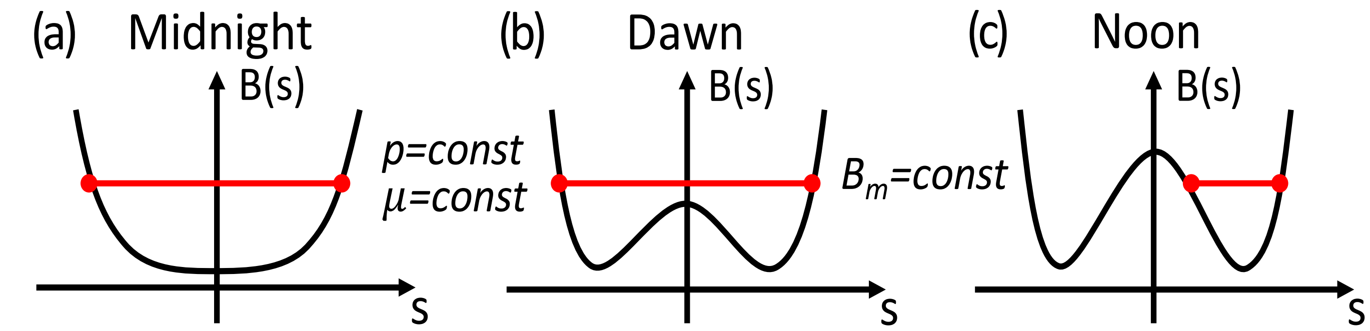
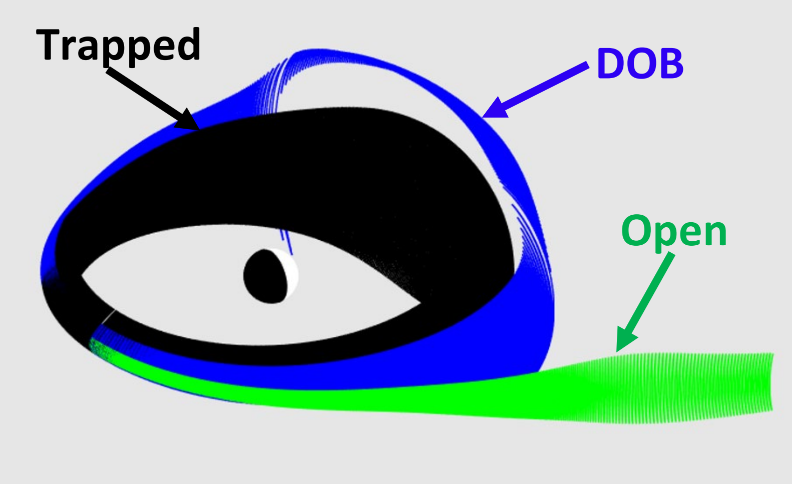
Pitch angle scattering by DOB

- Drift orbit bifurcation (DOB):
  - occurs when the dayside magnetosphere is compressed, exhibiting two local magnetic field minima where particles can be temporarily trapped

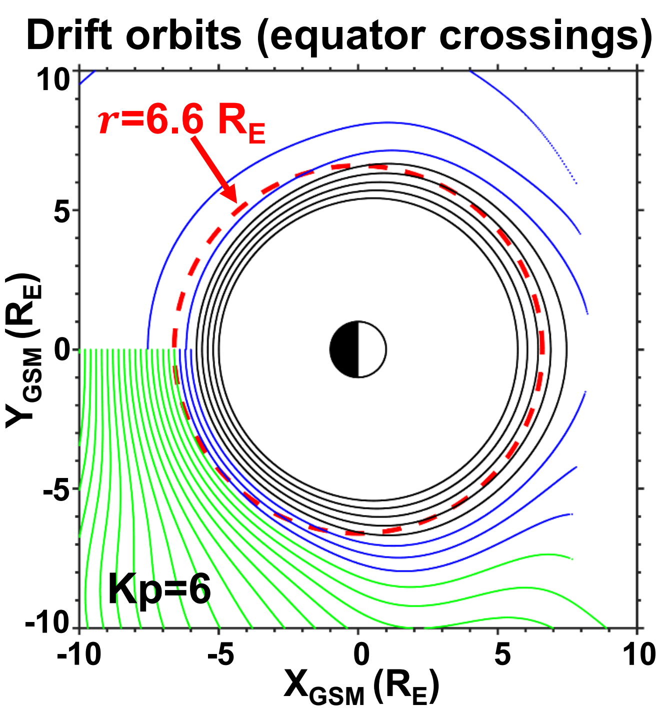


(Modified from Ukhorskiy+ [2011])

- Violate both the 2nd and 3rd adiabatic invariants, leading to fast radial transport and efficient pitch angle scattering
- More significant for higher pitch angle particles at larger L:
  - Could penetrate inside the geosynchronous orbit at Kp>=3 [Huang&Tu 2020]

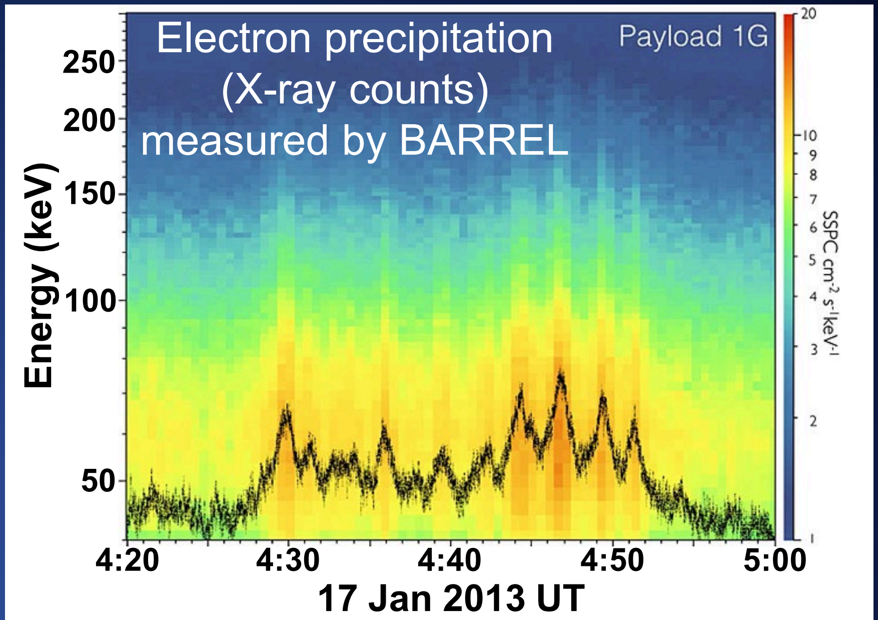


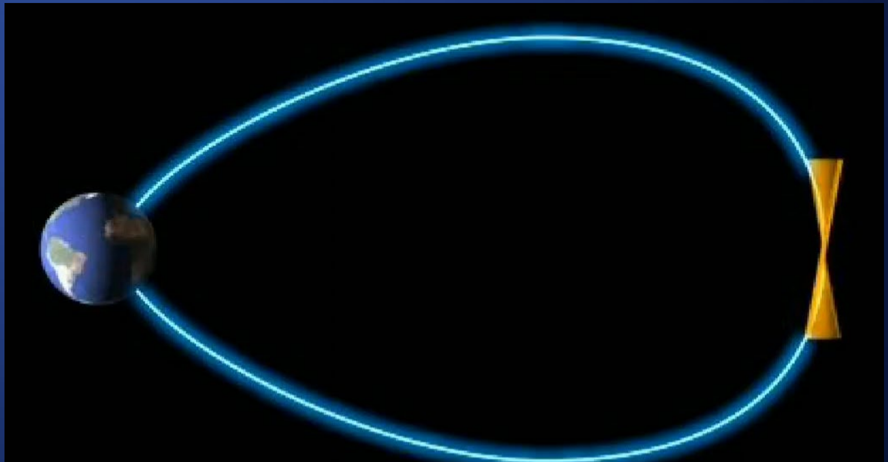
[Huang&Tu, GEM 2020]



Precipitation by enlarged loss cone

- Oscillations in relativistic electron precipitation observed by balloon measurements [Brito+ 2015]
  - Frequency: 1s to 10s mHz, ultralow frequency (ULF) waves
- Proposed mechanism
  - ULF waves drive inward transport of electrons → Loss cone gets bigger as L decreases → Precipitation
  - 1st and 2nd invariants are conserved
- Dependency: need some mechanism to move particles near the loss cone





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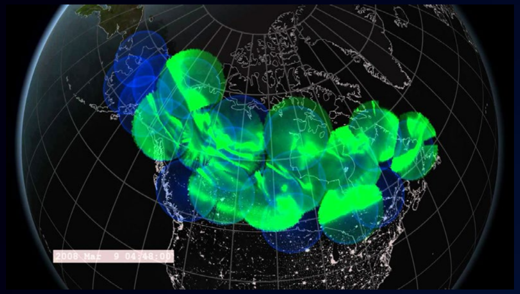
Types of precipitation observations

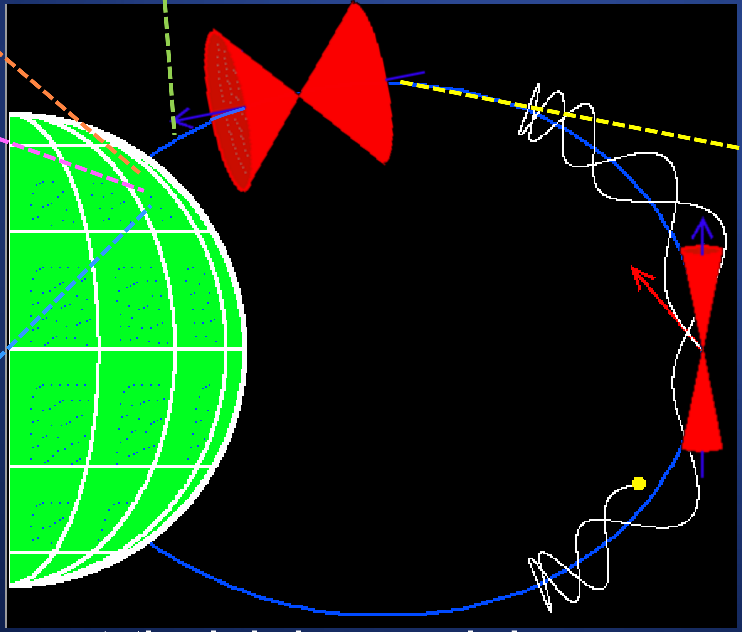


All-sky-imagers
Auroral intensity

Riometers
Energetic particle precipitation

Radars
Energetic particle precipitation

Balloons (e.g., BARREL)
Precipitating electron flux

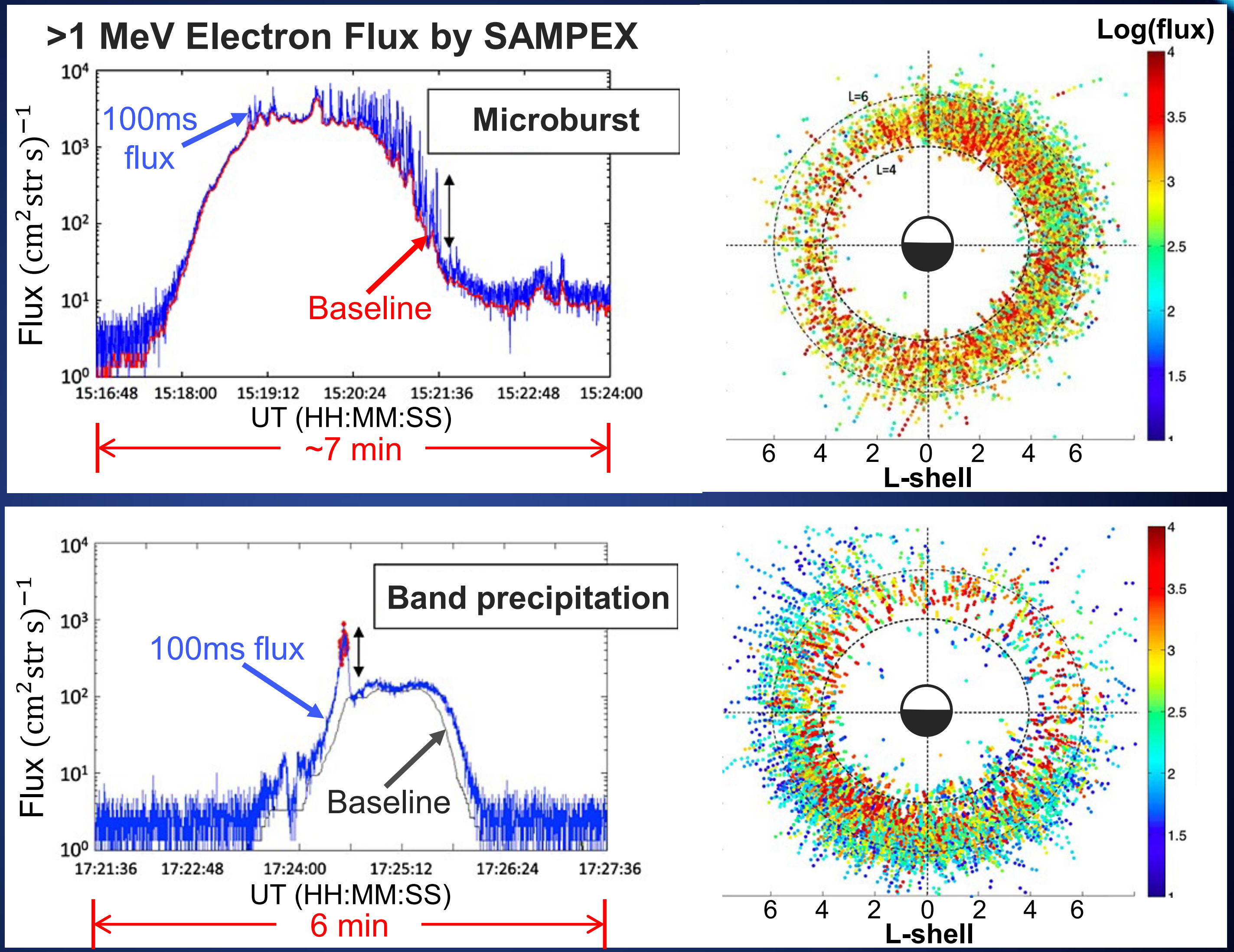


LEO satellites (e.g., SAMPEX, POES, CubeSats)
Particle flux near or inside the loss cone

– Bounce loss cone opens up at low altitudes

LEO: Band precipitation vs. Microburst

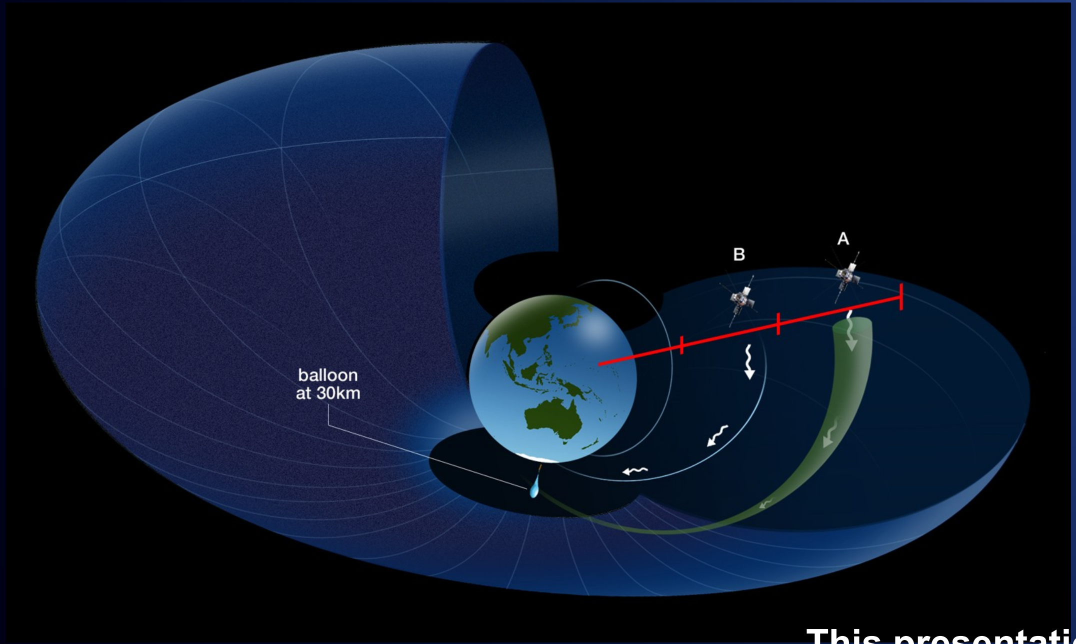
- Microburst
  - rapid bursts (~100 ms) of electron precipitation
  - most frequent on the dawn side, scattering by chorus waves
- Band precipitation
  - longer-duration (>10s sec) precipitation
  - most intense on the dusk side, scattering by EMIC waves
- Both are rapid precipitation, able to produce substantial radiation belt electron losses

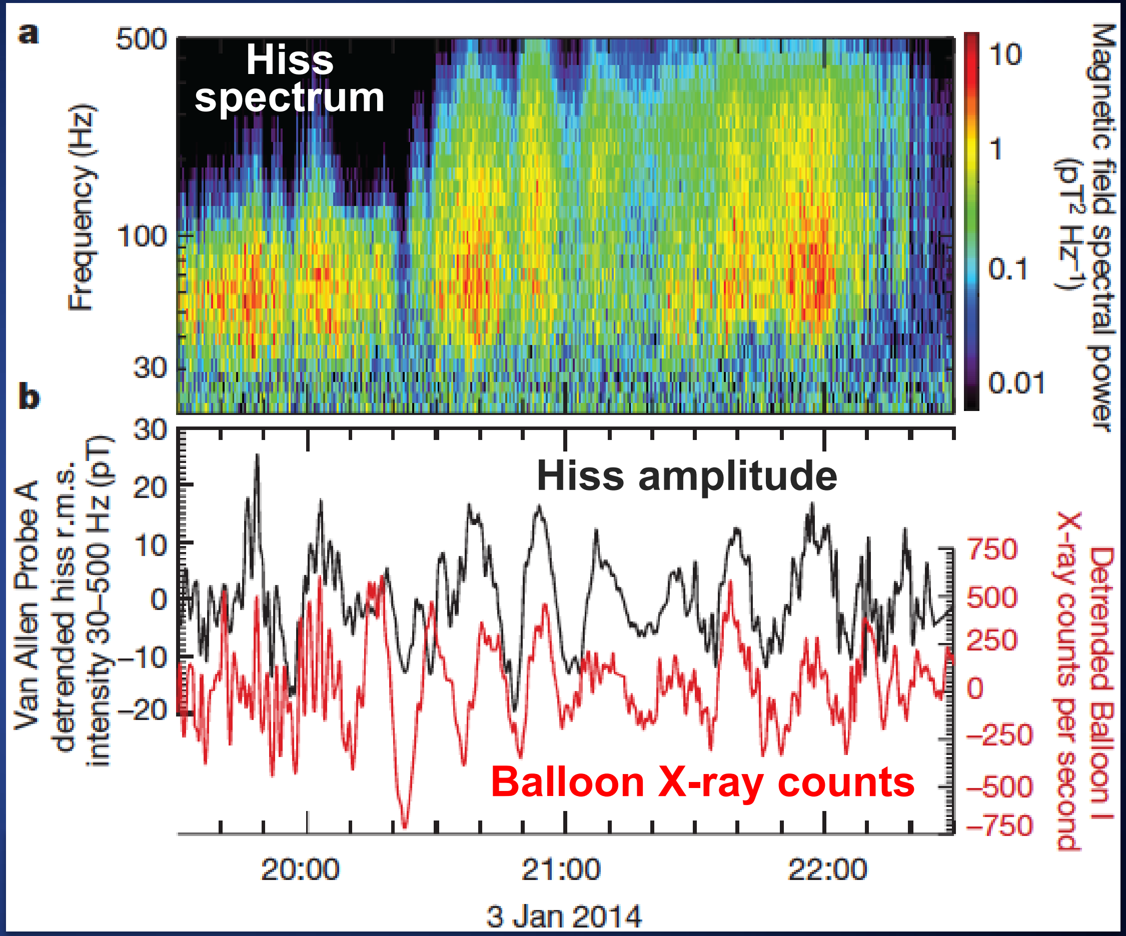


[Blum+ 2015]

Balloon: Precipitation and hiss

- X-ray counts observed by BARREL and plasmaspheric hiss observed by Van Allen Probes show a global-scale coherence.
  - Suggesting energetic electron precipitation driven by hiss waves
  - Scale: ΔMLT=6hr, ΔL=3.5 (multiple payloads)



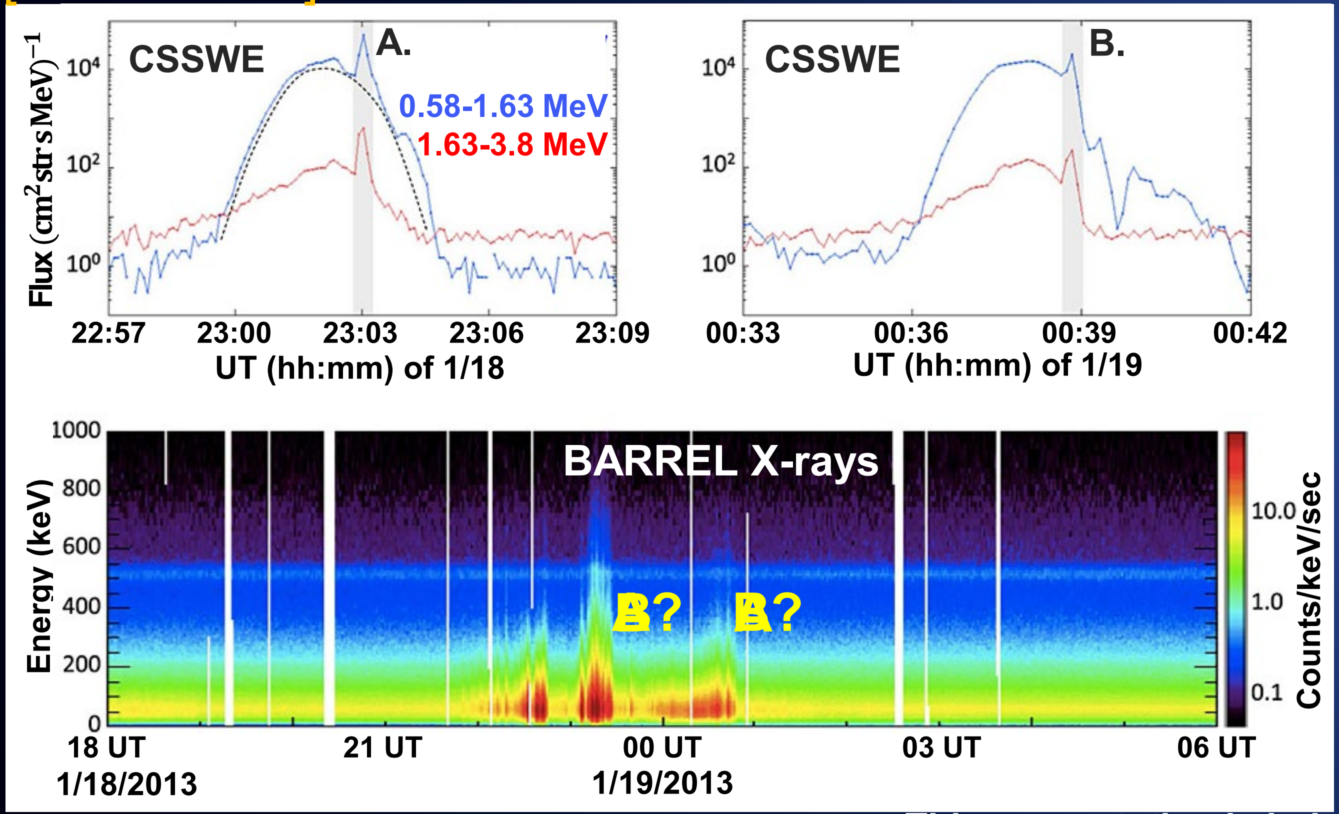


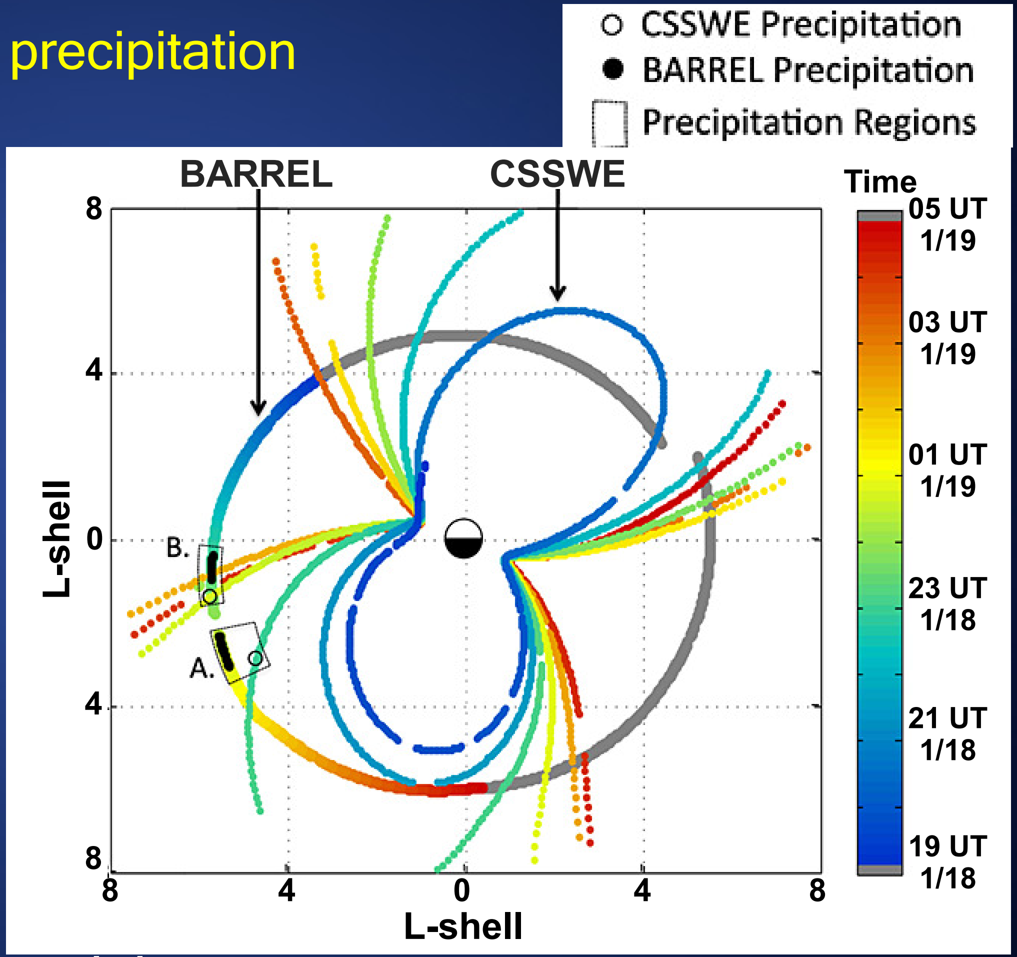
[Breneman+ 2015]

LEO & Balloon: Scale of precipitation

- Conjunctive CubeSat and balloon measurements of precipitation
  - Precipitation bands observed at LEO by CSSWE and by BARREL
  - Used to estimate the spatial and temporal scales of precipitation

[Blum+ 2013]





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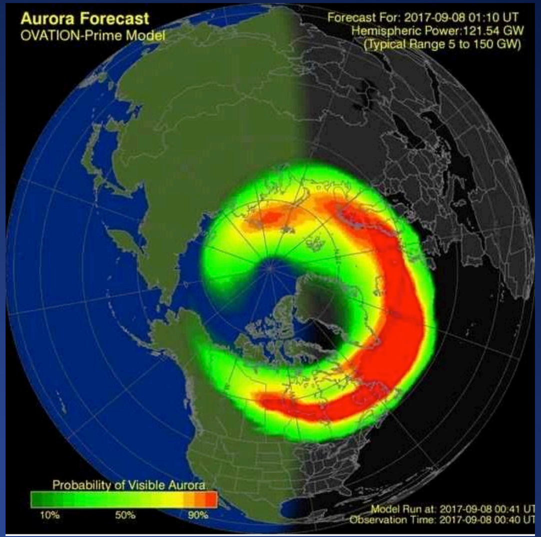
Types of precipitation models

- Empirical models [e.g., Newell+ 2014]
- MHD parameterization [e.g., Zhang+ 2015]
- Kinetic models
  - Diffusion-type models
  - Test particle codes



[Courtesy: NOAA, OVATION Prime model]

Inputs

Solar wind parameters: v, IMF B, clock angle

→

Outputs

Aurora energy flux & number flux

Pros:

- Easy to use, global specification and forecast

Cons:

- Empirically averaged (lack small-scale, fast variations)

Types of precipitation models

- Empirical models [e.g., Newell+ 2014]
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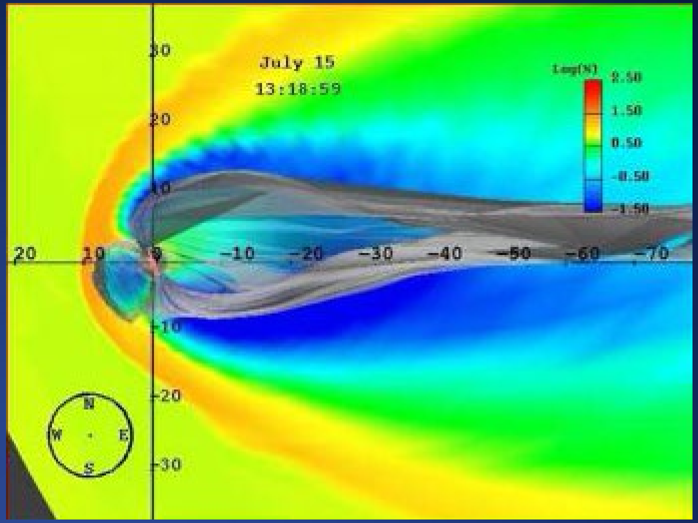

[Courtesy: HAO, LFM MHD code]

Inputs

MHD parameters:
T_e, N_e, $J_{||}$, B

Outputs

Precipitation energy flux & energy

Pros:

- Self-contained in MHD codes, global specification

Cons:

- Approximate, not including kinetic processes

Types of precipitation models

- Empirical models [e.g., Newell+ 2014]
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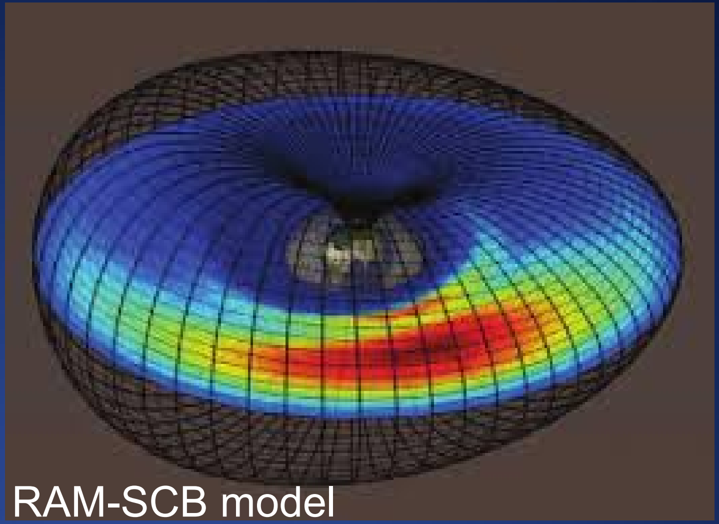


[Courtesy of V. Jordanova]

Inputs

Diffusion coefficients
Global E&B models

→

Outputs

flux(E, α ,r,Φ,time)

Pros:

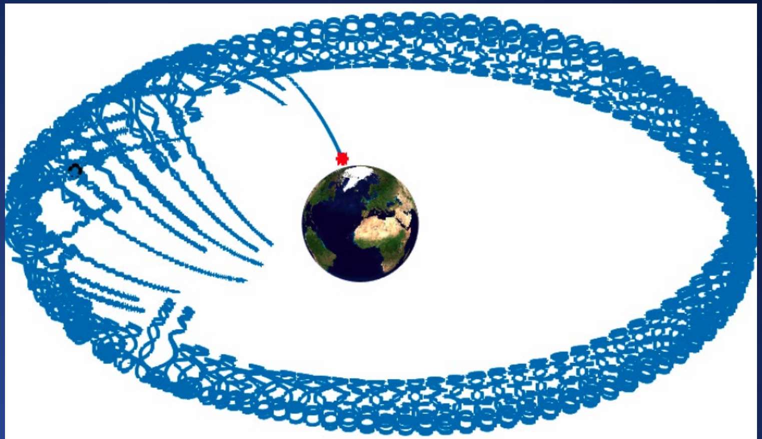
- Physics-based, include kinetic processes, efficient

Cons:

- Assumptions of quasi-linear theory and diffusion physics

Types of precipitation models

- Empirical models [e.g., Newell+ 2014]
- MHD parameterization [e.g., Zhang+ 2015]
- Kinetic models
  - Diffusion-type models
  - Test particle codes



[Eshetu+, 2020]

Inputs

Global E&B models or Analytical wave models

Outputs

Subset of flux(E, α, r, Φ, time)

Pros:

- No diffusion assumption, include nonlinear processes

Cons:

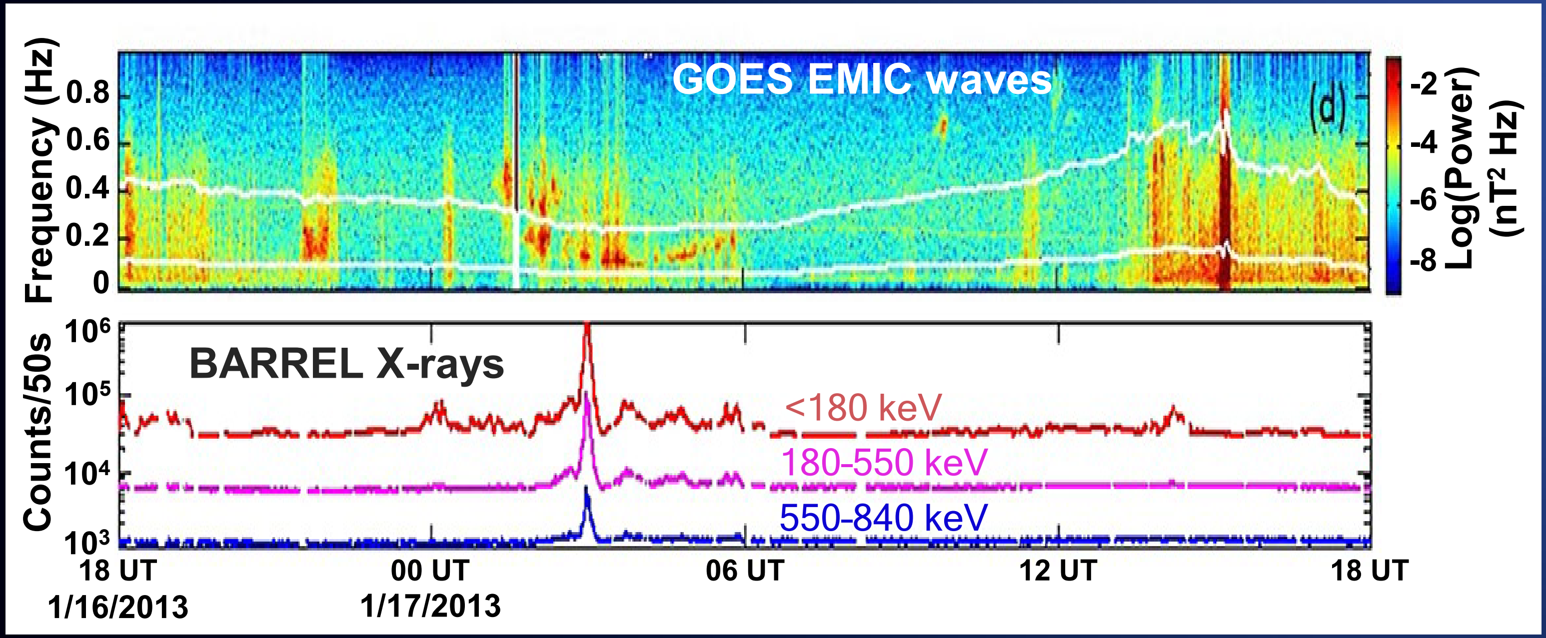
- Computational expensive, difficult to be global

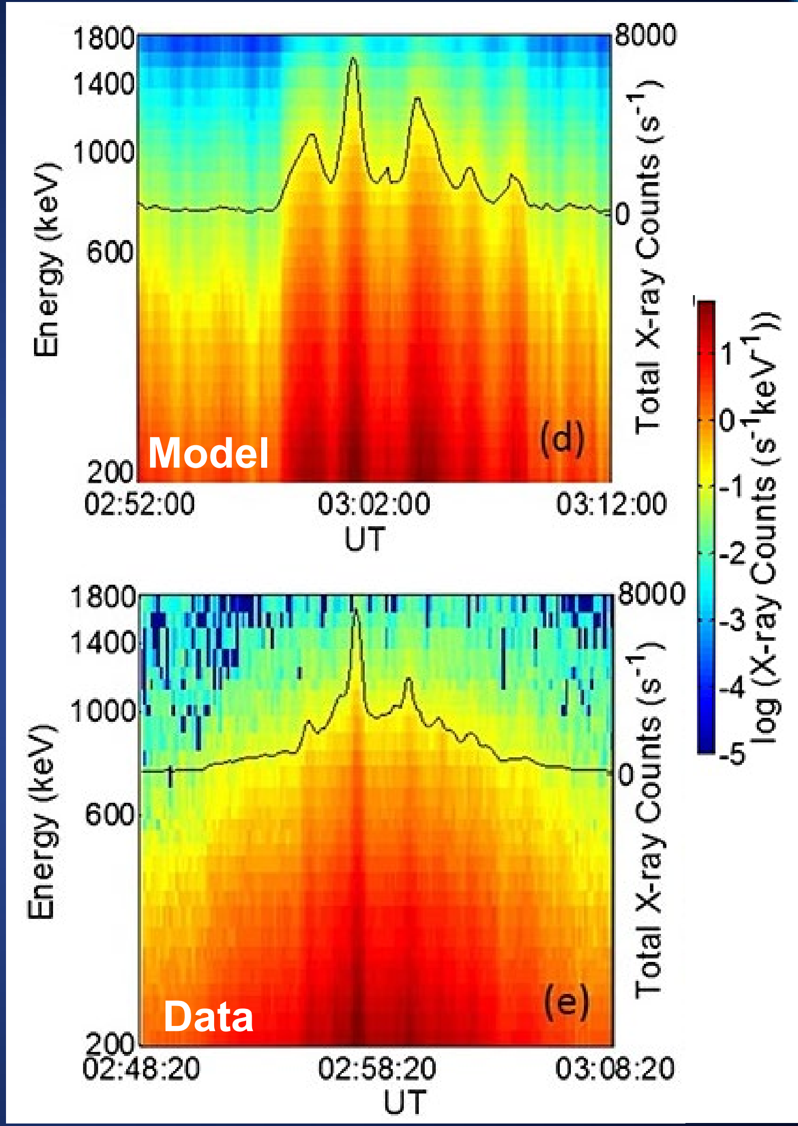
1D Pitch-Angle diffusion model

- Model equation: [Li+ 2014]

At given L and energy: $$\frac{\partial f}{\partial t} = \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) - \frac{f}{\tau}$$

- Diffusion coefficient derived from wave data
- Used to simulate local precipitation





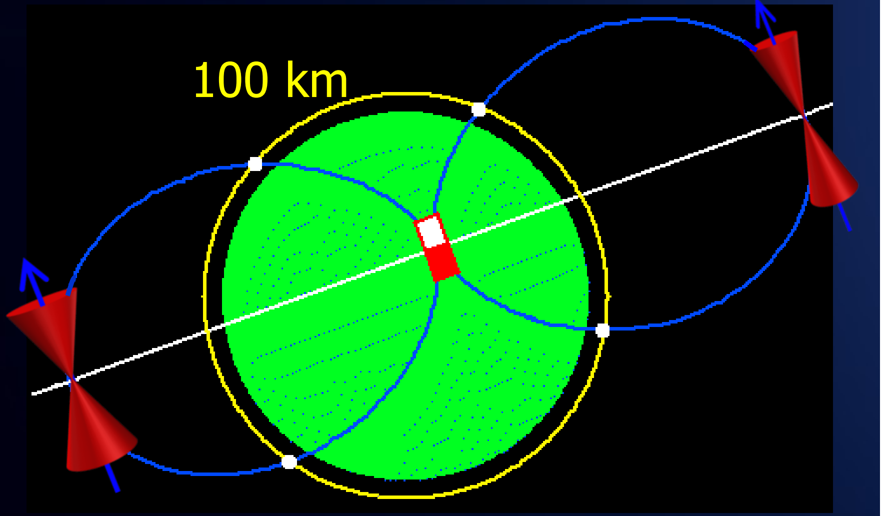
2D Drift-Diffusion model

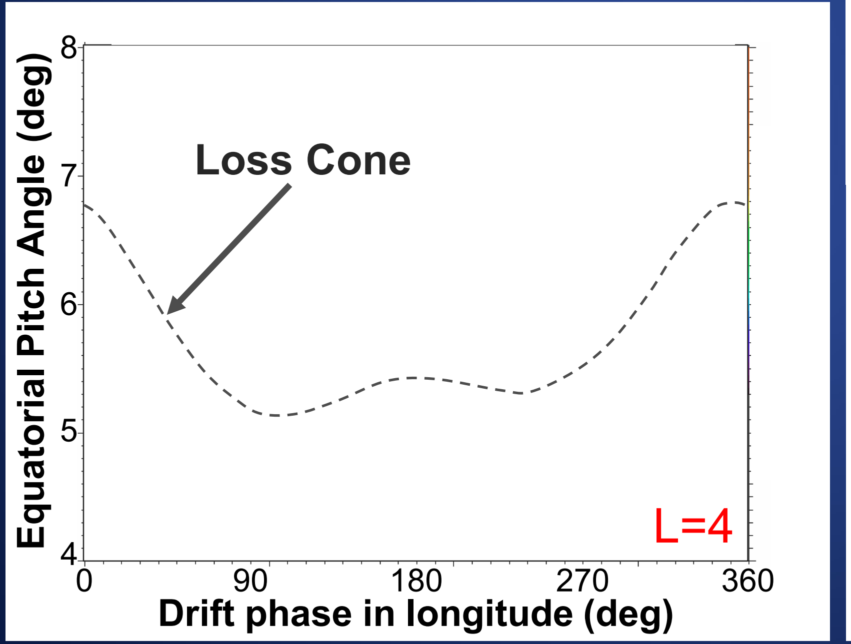
- Model equation: [Selesnick+ 2020; Tu+ 2010]

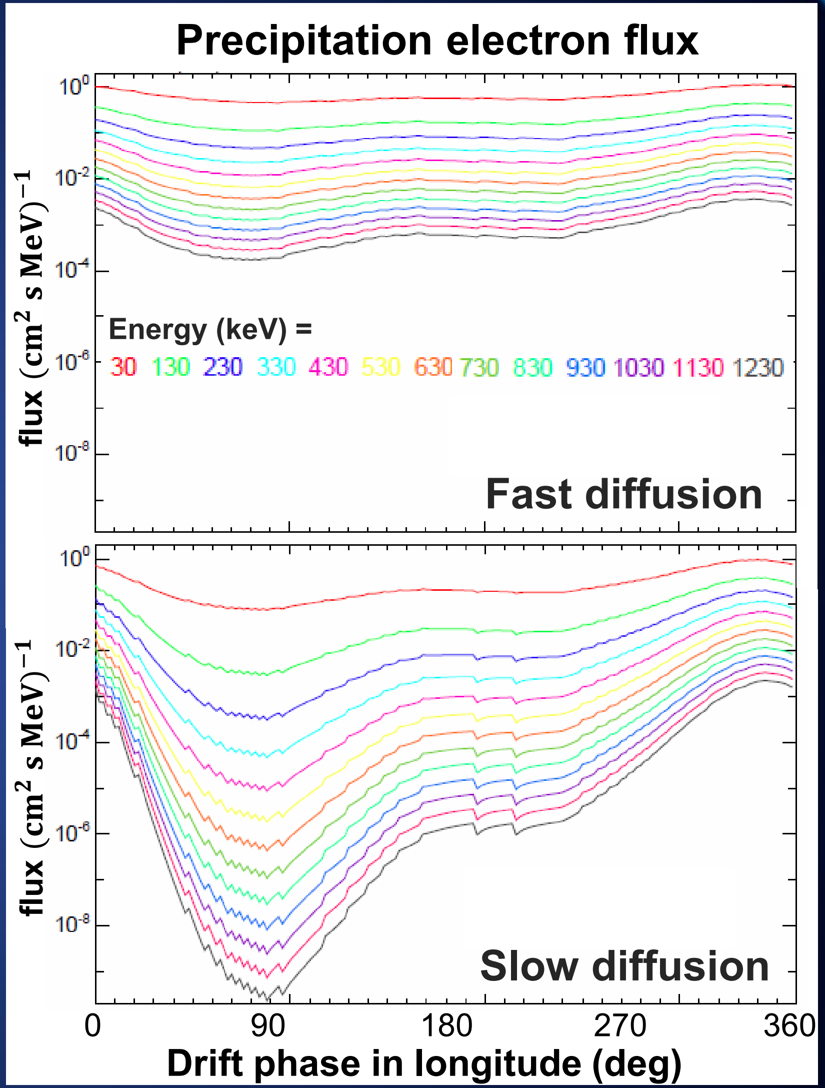
At given L and energy: $$\frac{\partial f}{\partial t} + \omega_d \frac{\partial f}{\partial \varphi} = \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) + \cdots$$

- Diffusion coefficient determined by best fitting LEO data
- Used to simulate global precipitation

Longitude-dependent loss cone







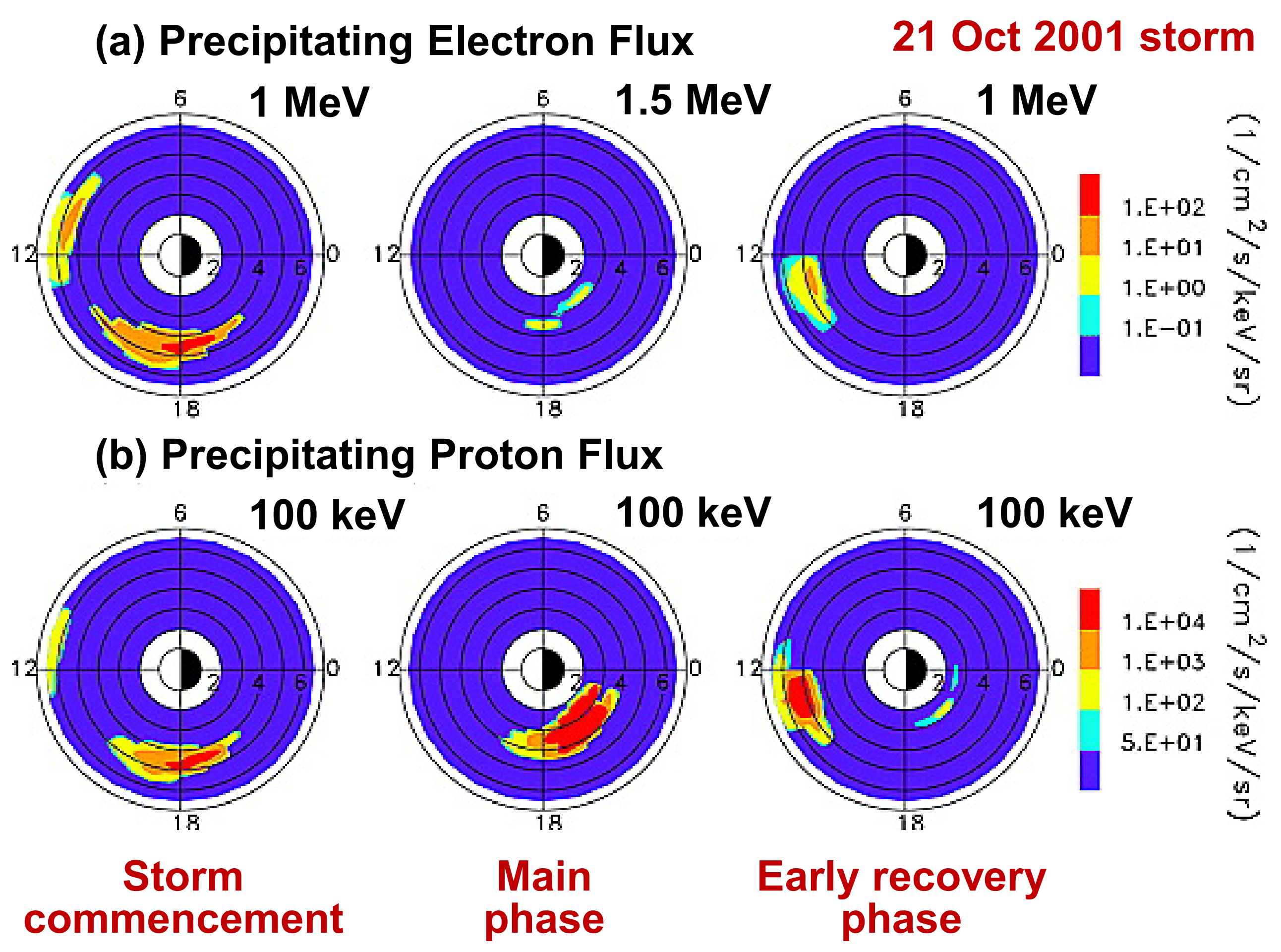
4D Advection-Diffusion model

- Model equation: [Jordanova+ 2008]

$$\frac{\partial f}{\partial t} + \frac{1}{R_0^2}\frac{\partial}{\partial R_0}\left(R_0^2 \langle\frac{dR_0}{dt}\rangle f\right) + \frac{\partial}{\partial \varphi}\left(\langle\frac{d\varphi}{dt}\rangle f\right) + \frac{1}{\sqrt{E}}\frac{\partial}{\partial E}\left(\sqrt{E}\langle\frac{dE}{dt}\rangle f\right) + \frac{1}{h\mu_0}\frac{\partial}{\partial \mu_0}\left(h\mu_0\langle\frac{d\mu_0}{dt}\rangle f\right) = \langle\left(\frac{\partial f}{\partial t}\right)_{rd}\rangle + \boxed{\langle\left(\frac{\partial f}{\partial t}\right)_{loss}\rangle}$$

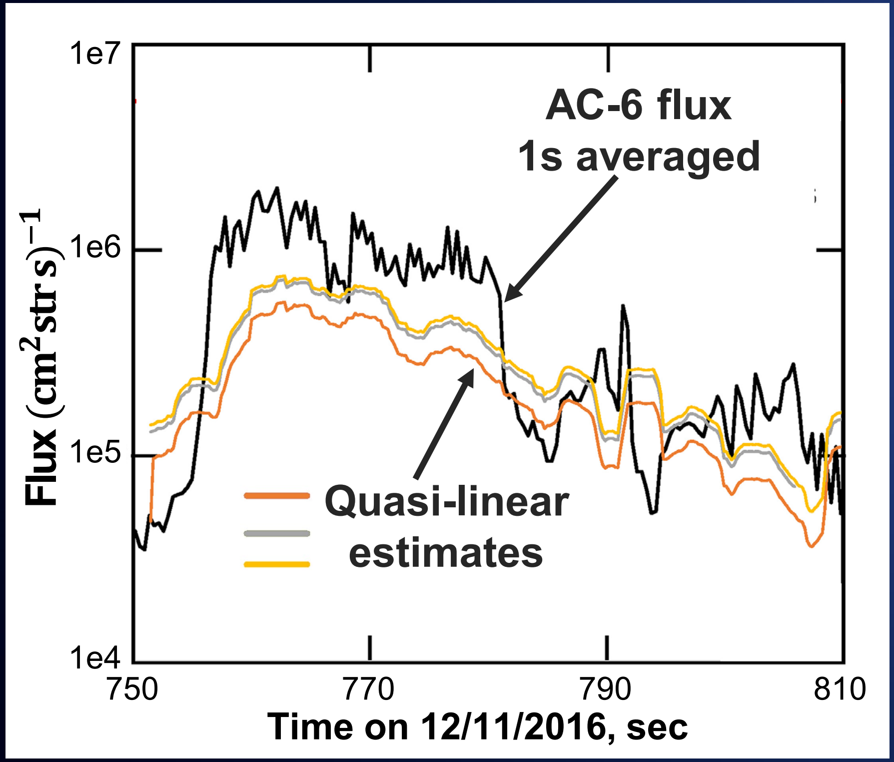
Wave scattering: $$\langle\left(\frac{\partial f}{\partial t}\right)_{wp}\rangle = \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right)$$

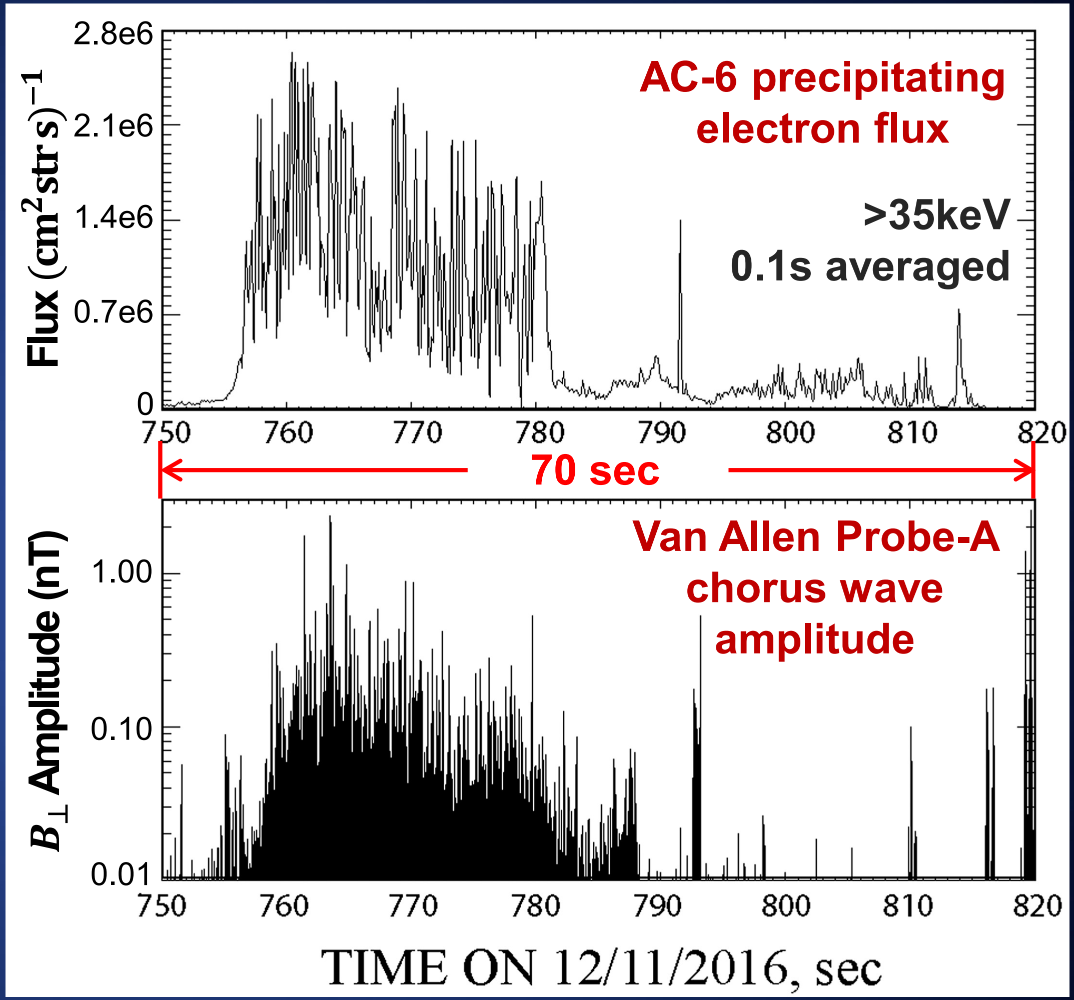
- Explicitly model the source and transport across L and energies
- Used to simulate global precipitation



Limit of diffusion model

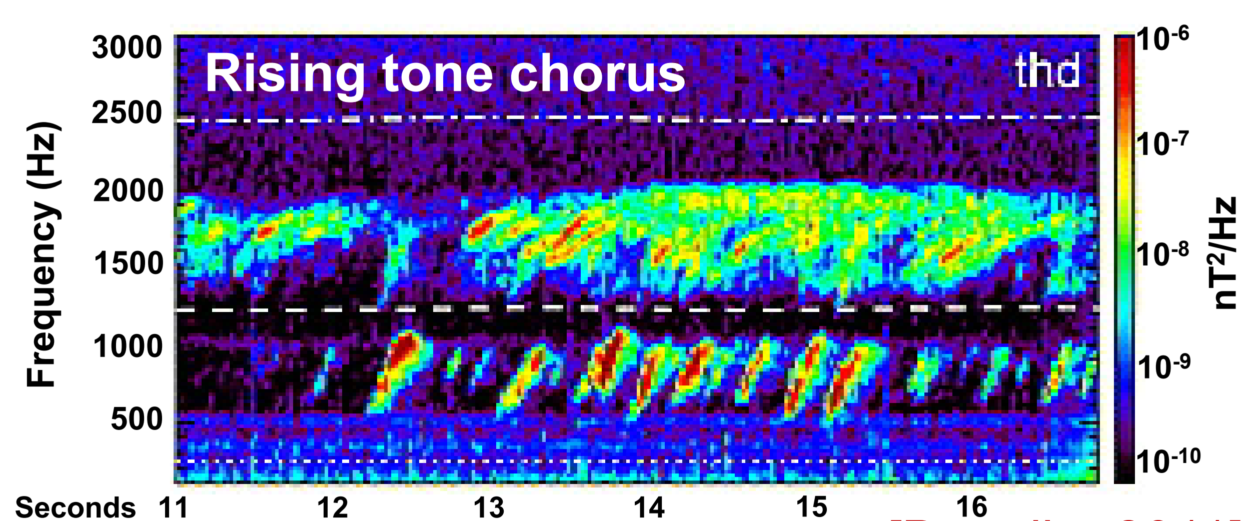
- Microburst precipitation simulated by quasi-linear diffusion [Mozer+ 2018]
- Unable to reproduce the fast burst of precipitation by large-amplitude chorus



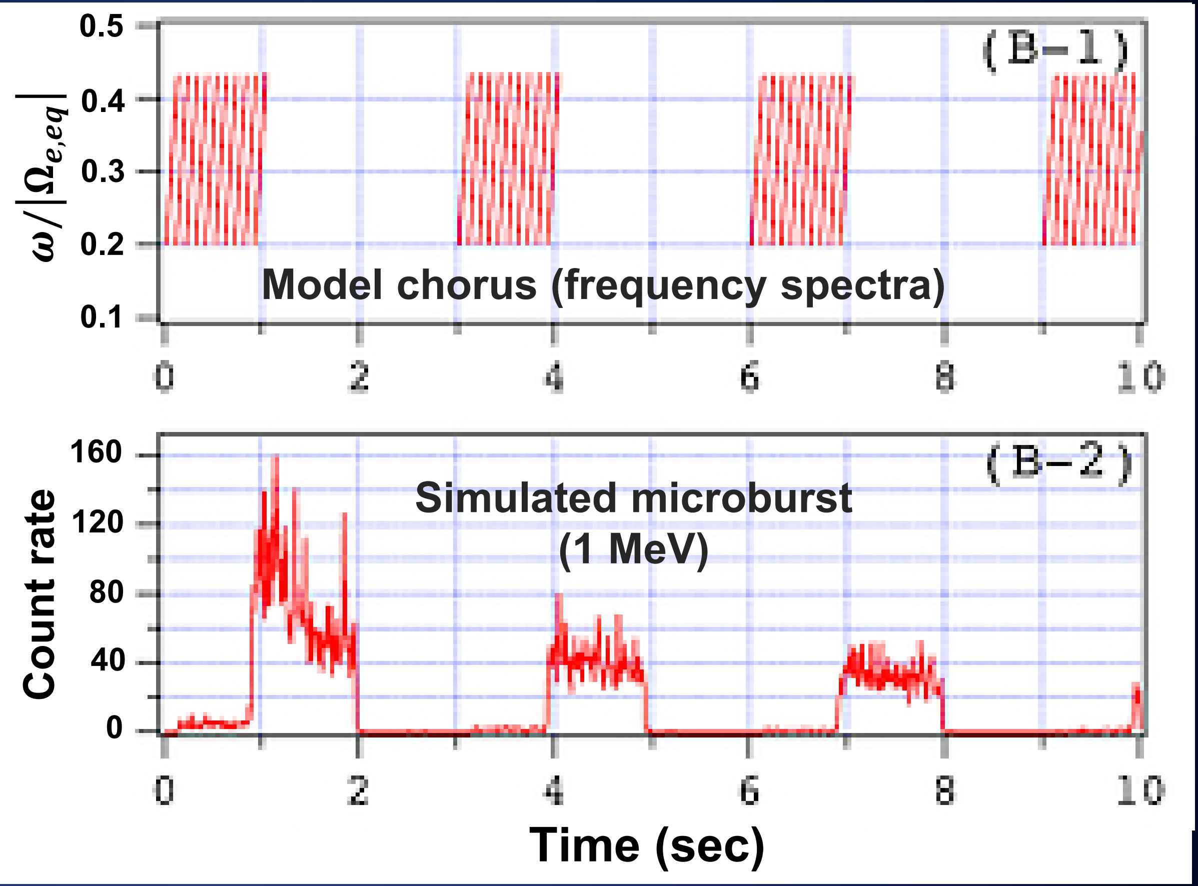


Test particle simulation

- Microburst simulated by a 3D test particle simulation [Saito+ 2012]
- Resonant interactions with rising-tone elements of chorus at high latitudes produce bursty precipitation of relativistic electron.



[Bortnik+ 2011]



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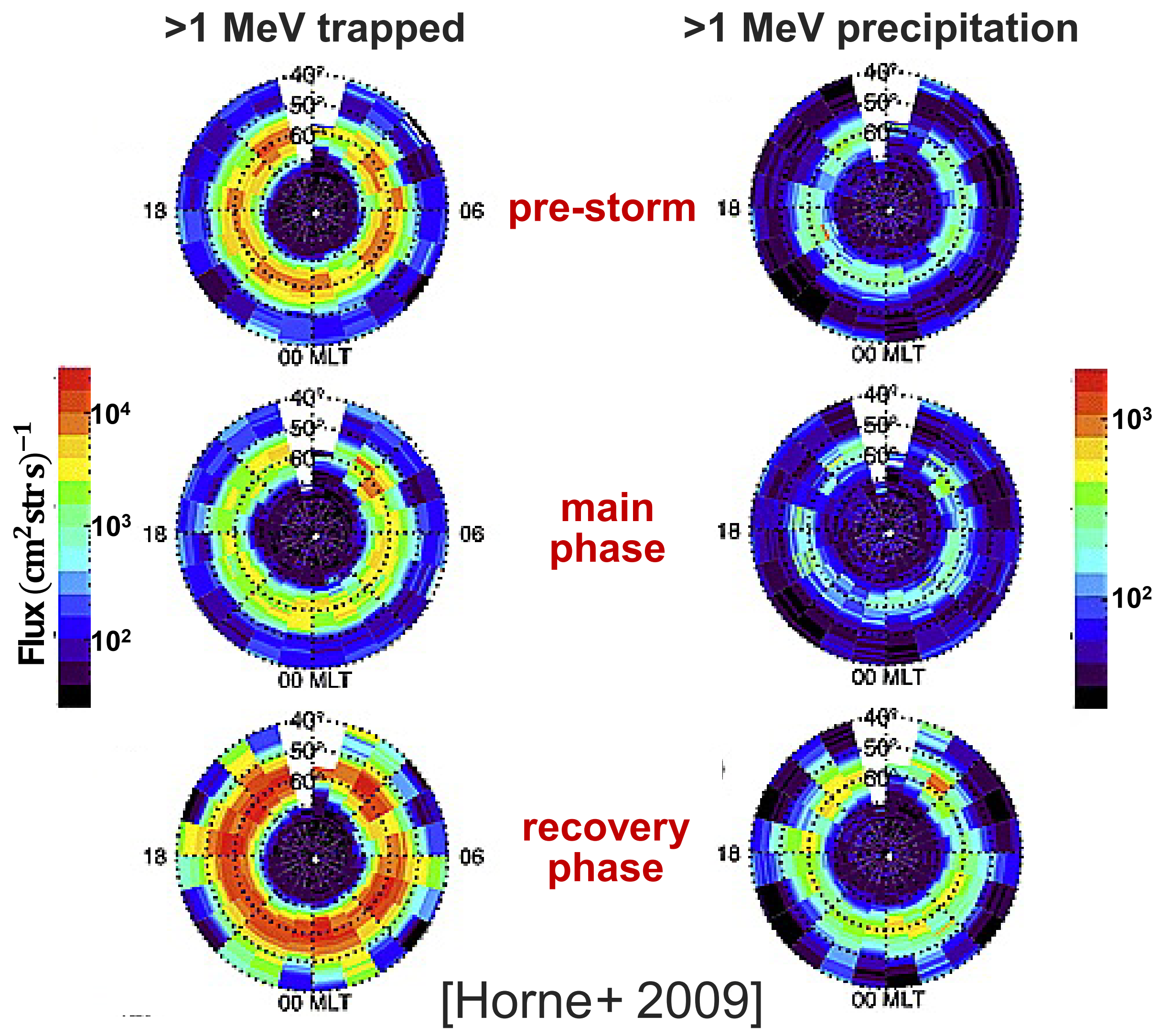
Contribution of precipitation to loss

- Correlated?
  - Loss with no precipitation & Precipitation with no loss
- To resolve the contribution of precipitation to energetic particle losses, we need:
  - Models that link high-altitude loss with low-altitude precipitation
  - Realistic model inputs of waves, plasma, and fields
  - Global observation of waves



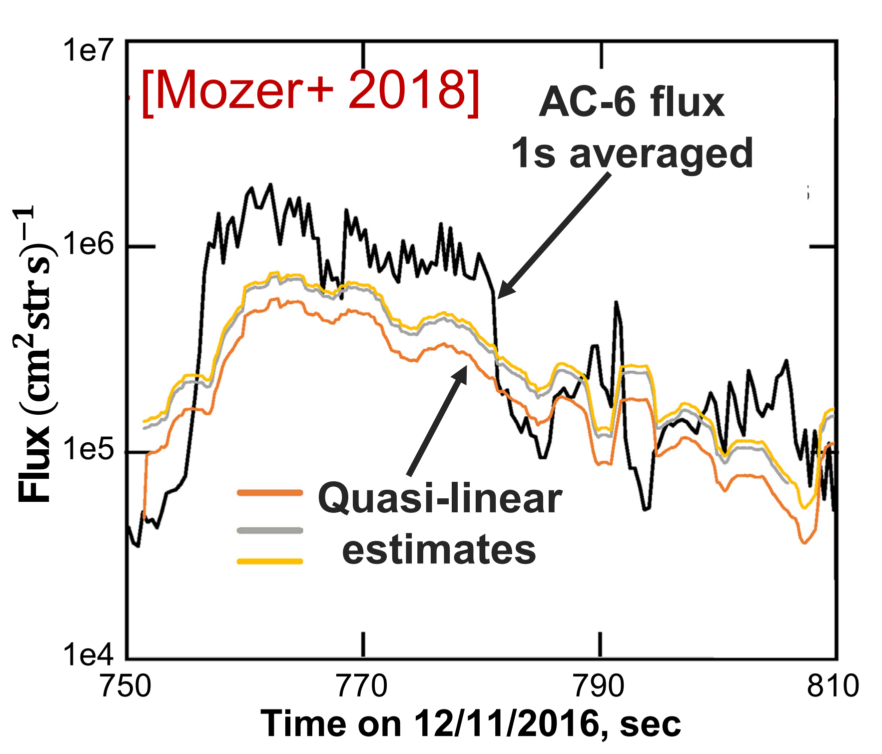
[Horne+ 2009]

Quantification of global precipitation

Model + Data → Global precipitation

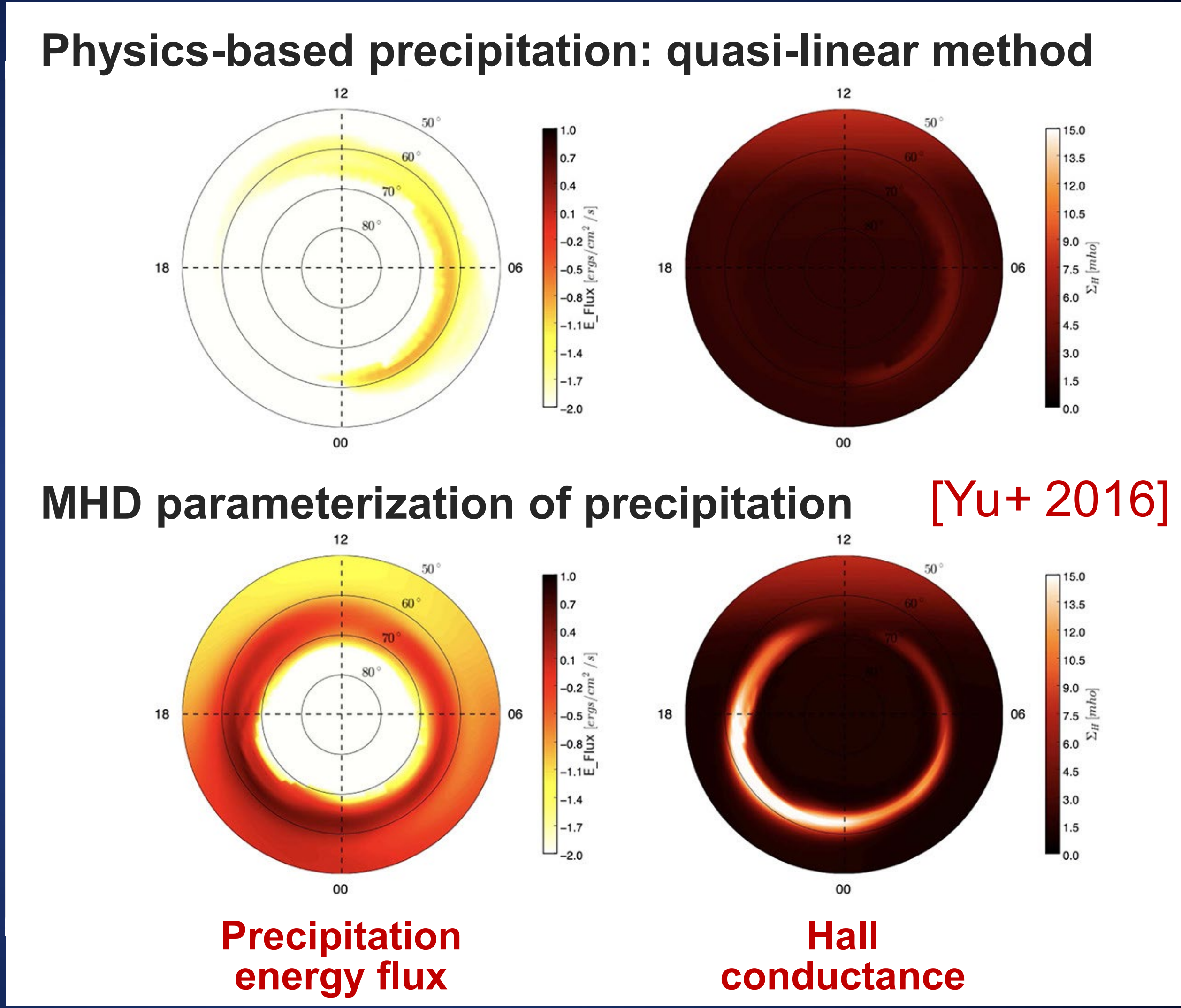
- Better inputs into the quasilinear model
- Incorporate new physics (non-linear)

- Combine all data (LEO, balloons, riometer …)
- More data with better time and energy resolutions



Towards self-consistent coupling

- Self-consistent and global modeling of magnetosphere-ionosphere coupling
  - Couple physical models of precipitation into models of ionospheric electrodynamics
  - Better understand the feedback effects on magnetospheric dynamics



Summary and Conclusions

- Precipitation of energetic particles plays an important role in magnetospheric dynamics, M-I coupling, and atmospheric chemistry.
- It is driven by various mechanisms that scatter the particle pitch angle or enlarge the loss cone.
- Great observational and modeling progress has been made in quantitative characterization of precipitation.
- Challenges in understanding and quantifying global precipitation and self-consistent modeling of M-I coupling.