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Title:	Modeling Radiation Belt Electron Dynamics with the DREAM3D Diffusion Model
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Intended for:	Talk slides for personal job interview based on the two published JGR and GRL papers with approved LA-UR numbers.
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Modeling Radiation Belt Electron Dynamics with the DREAM3D Diffusion Model

Weichao Tu[1], G. Cunningham[1], Y. Chen[1], M. Henderson[1], S. K. Morley[1], G.D. Reeves[1], J.B. Blake[2], D.N. Baker[3], and H. Spence[4]

[1]Los Alamos National Laboratory

[2]The Aerospace Corporation

[3]Laboratory for Atmospheric and Space Physics

[4]University of New Hampshire

Part 1: Long-term simulation of the GEM challenge intervals

- "Global Radiation Belt Modeling Challenge"
  - Organized by NSF/GEM "Radiation Belts and Wave Modeling" focus group
- Training interval
  - Aug. 15th to Oct. 15th ,1990
- Challenge interval
  - Feb. 1st to Aug. 1st, 1991
- Published in Tu et al. [JGR 2013]

DREAM3D Diffusion Model

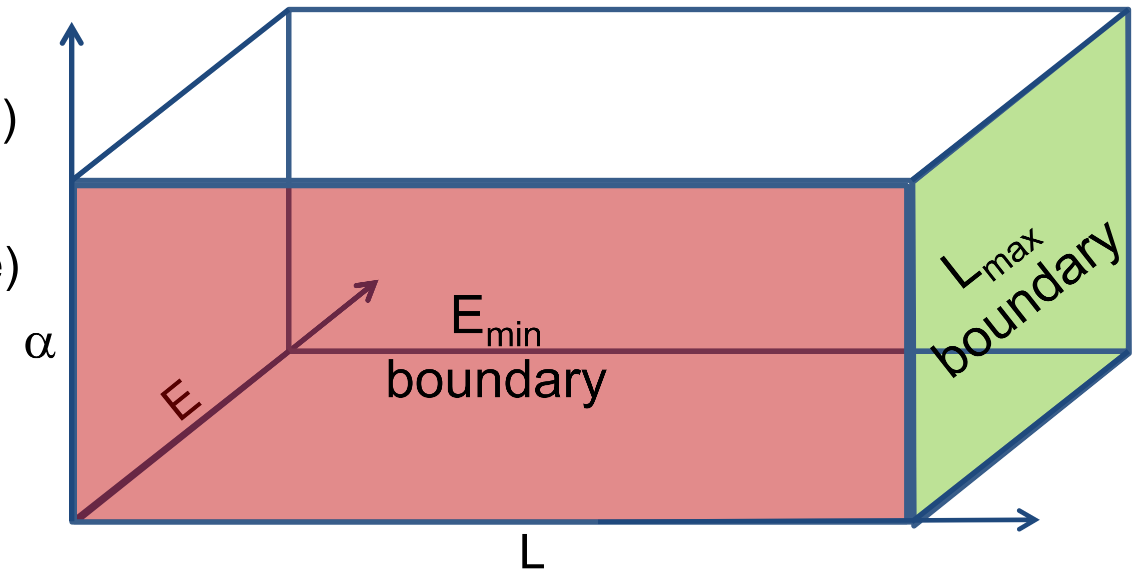
$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) + \frac{1}{G}\frac{\partial}{\partial \alpha}\left(G D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) - \frac{f}{\tau}$$
$$+ \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{p\alpha}\frac{\partial f}{\partial \alpha}\right) + \frac{1}{G}\frac{\partial}{\partial \alpha}\left(G D_{\alpha p}\frac{\partial f}{\partial p}\right)$$

$$G = T(\alpha)\sin(2\alpha),\ T(\alpha) \approx 1.38 - 0.32(\sin\alpha + \sqrt{\sin\alpha})$$

Boundary Conditions needed on 6 surfaces

$\alpha=0$	PSD=0 (atmosphere)
$\alpha=\pi/2$	dPSD/dα=0
L=1	PSD=0 (atmosphere)
$L=L_{max}$	outer boundary
$E=E_{max}$	PSD=0
$E=E_{min}$	seed population (100 KeV)

Calculational volume for 3D code



Diffusion Coefficients

- Radial diffusion: $D_{LL}(Kp)=D_{LL}^{M} + D_{LL}^{E}$ [Brautigam and Albert, 2000]

$$D_{LL}^{M} = 10^{0.506Kp-9.325} L^{10}, D_{LL}^{E} = \frac{1}{4}\left(\frac{c\widetilde{E}}{B_0}\right)^2\left[\frac{T}{1+(\omega_d T/2)^2}\right]L^6$$

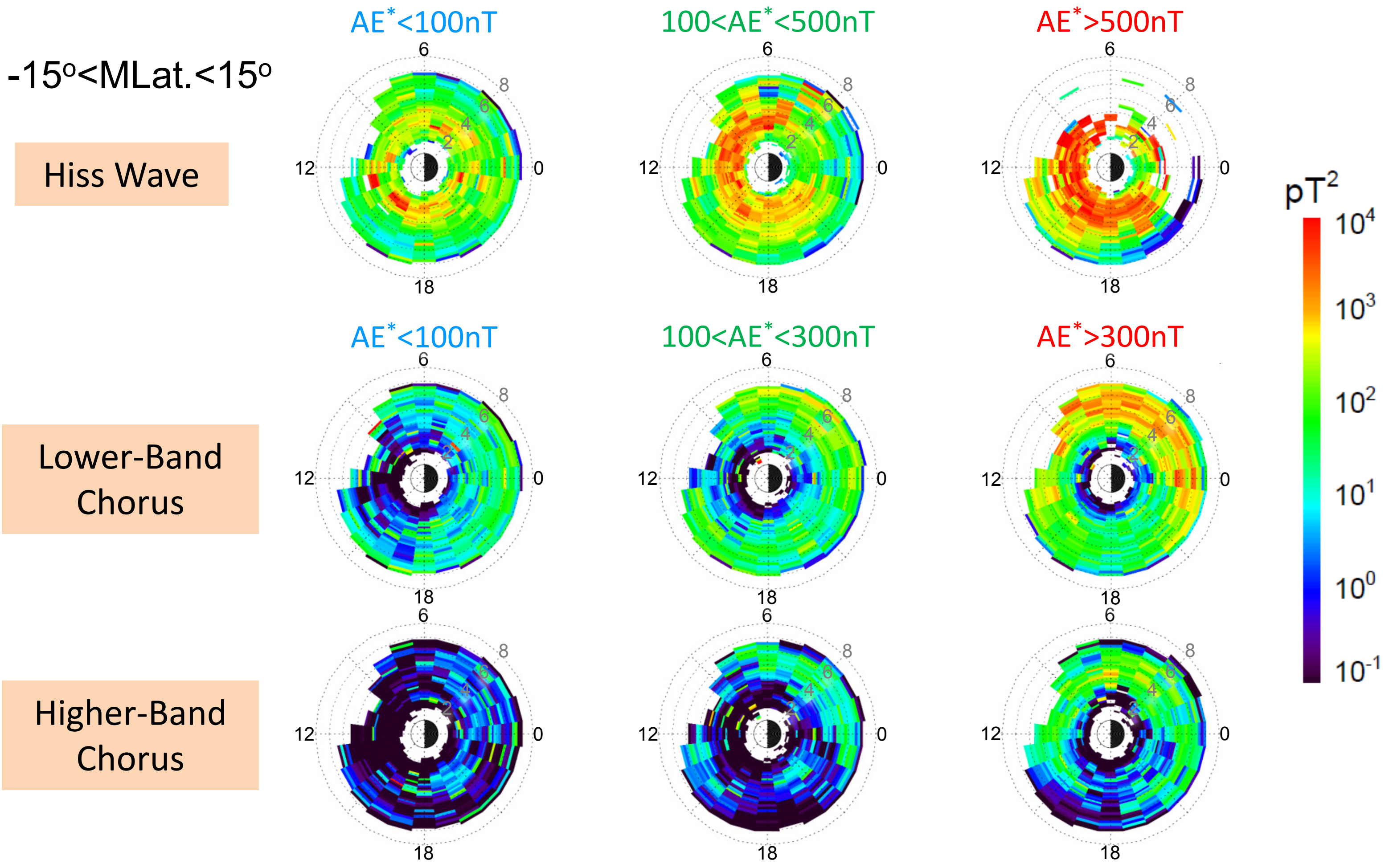
where $\widetilde{E}(Kp) = 0.26(Kp-1)+0.1\,\mathrm{mV/m}$

- Pitch angle, momentum, and mixed diffusion: $D\alpha\alpha$, Dpp, $D\alpha p$
  - Quasi-linear diffusion coefficients, bounce- and drift-averaged, assumed field-aligned waves [Summers et al., 2007a,b]
  - Wave and plasma parameters:

Waves	B_w	λ_{max}	MLT%	Wave Spectral Properties	Density Model
Lower-band Chorus				$\omega_m/\Omega_e = 0.3,\ \delta\omega/\Omega_e = 0.1$ $\omega_{uc}/\Omega_e = 0.5,\ \omega_{lc}/\Omega_e = 0.1$	$124(3/L)^4$
Higher-band Chorus	Dynamic Wave Model $B_w(\lambda, MLT, L, AE)$			$\omega_m/\Omega_e = 0.7,\ \delta\omega/\Omega_e = 0.1$ $\omega_{uc}/\Omega_e = 0.9,\ \omega_{lc}/\Omega_e = 0.5$	$124(3/L)^4$ [Sheeley, 2001]
Plasmaspheric hiss				$\omega_m = 600Hz,\ \delta\omega = 300Hz$ $\omega_{uc} = 2000Hz,\ \omega_{lc} = 300Hz$	$10^{-0.3145L+3.9043}$ [Carpenter and Anderson, 1992]

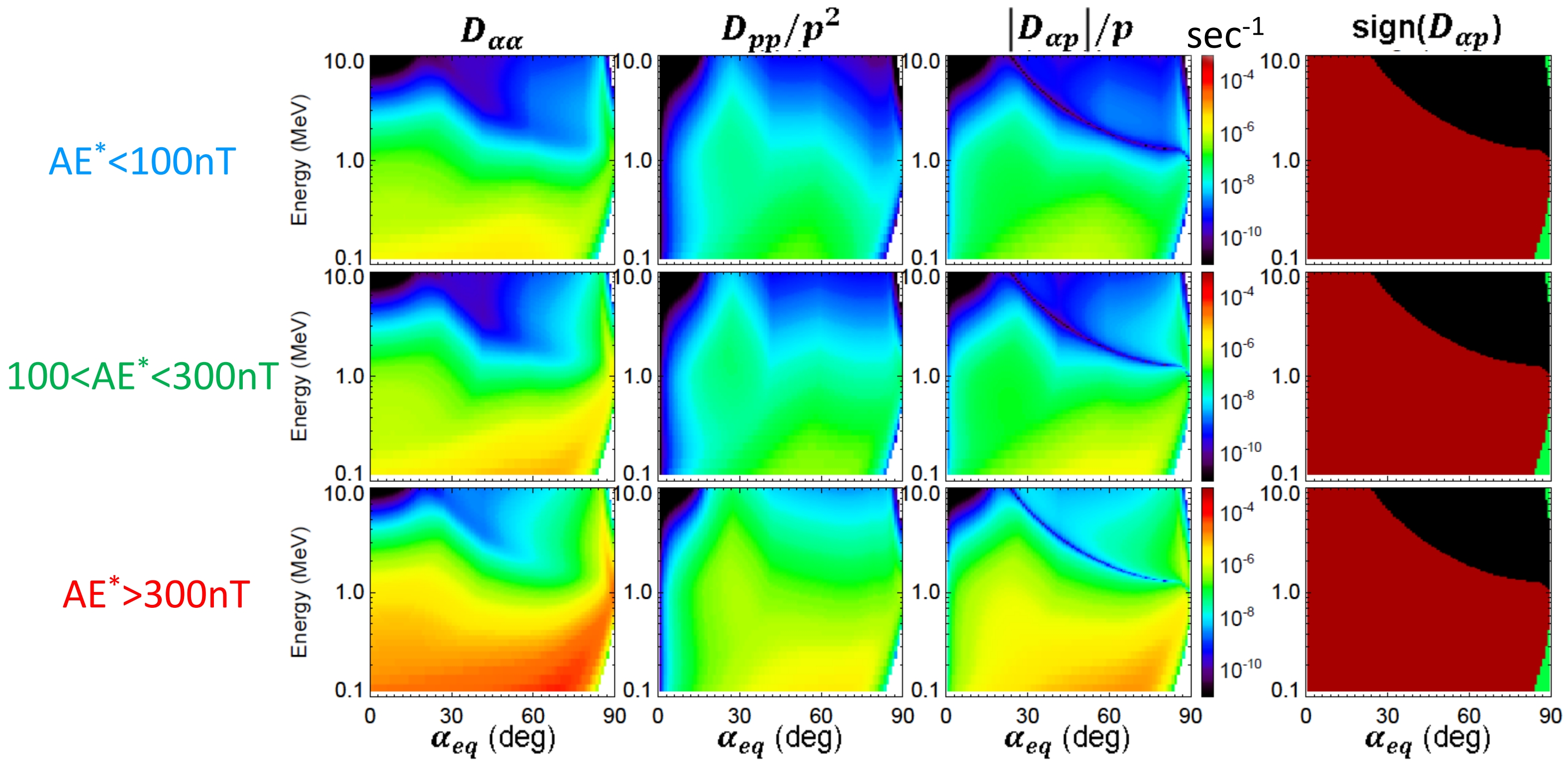
Dynamic Wave Model

- Use CRRES PWE data to developed whistler-mode hiss and chorus wave models.
- Model output: Wave Intensity (L-shell, MLT, Mag. Latitude, and AE* index)



Diffusion Coefficients

- Calculated diffusion coefficients for lower-band chorus at L=4.5



Model Results: GEM training interval

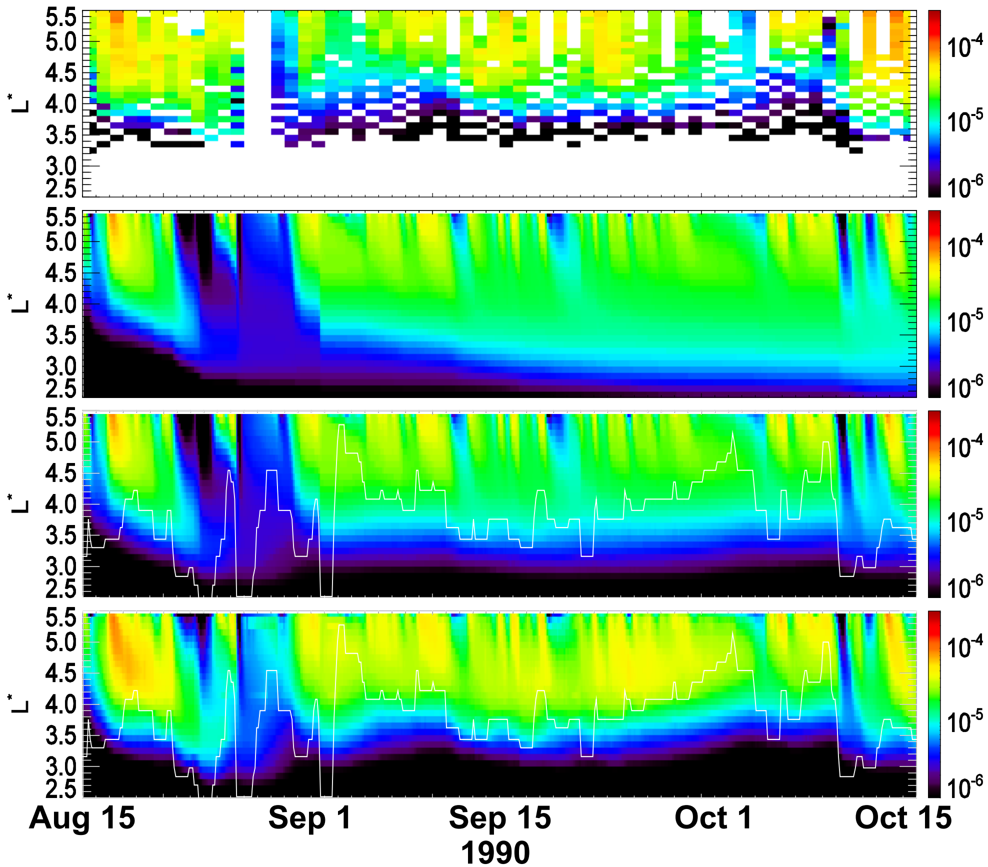
- Use CRRES data for outer boundary condition at $L^*=5.5$ and initial condition.

μ=523 MeV/G,
K=0.03 $G^{1/2}$Re
PSD data

RD only

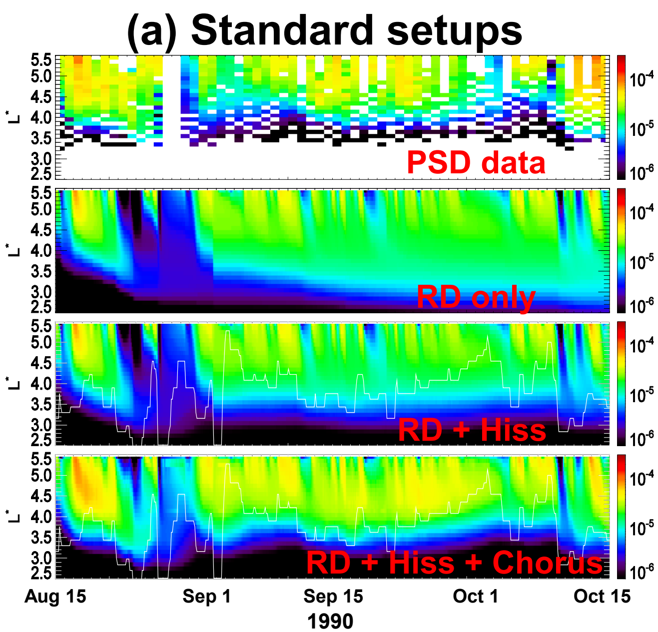
RD + Hiss

RD + Hiss + Chorus



White curve: Plasmapause location [Carpenter and Anderson, 1992]

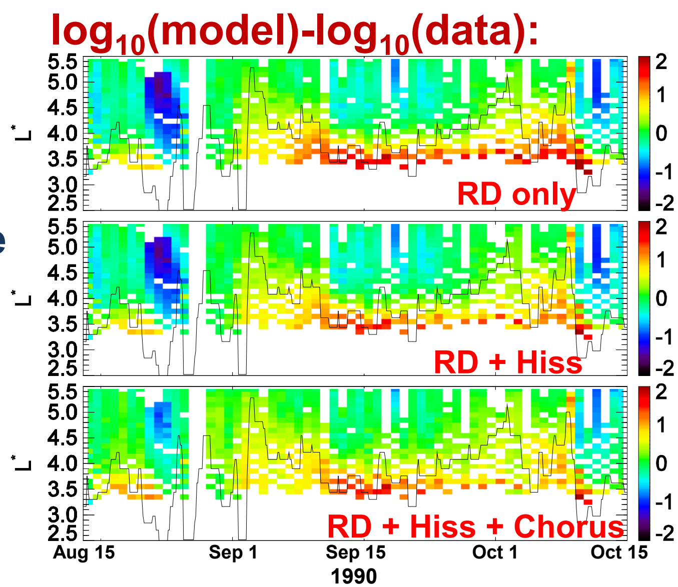
Model Results: GEM training interval



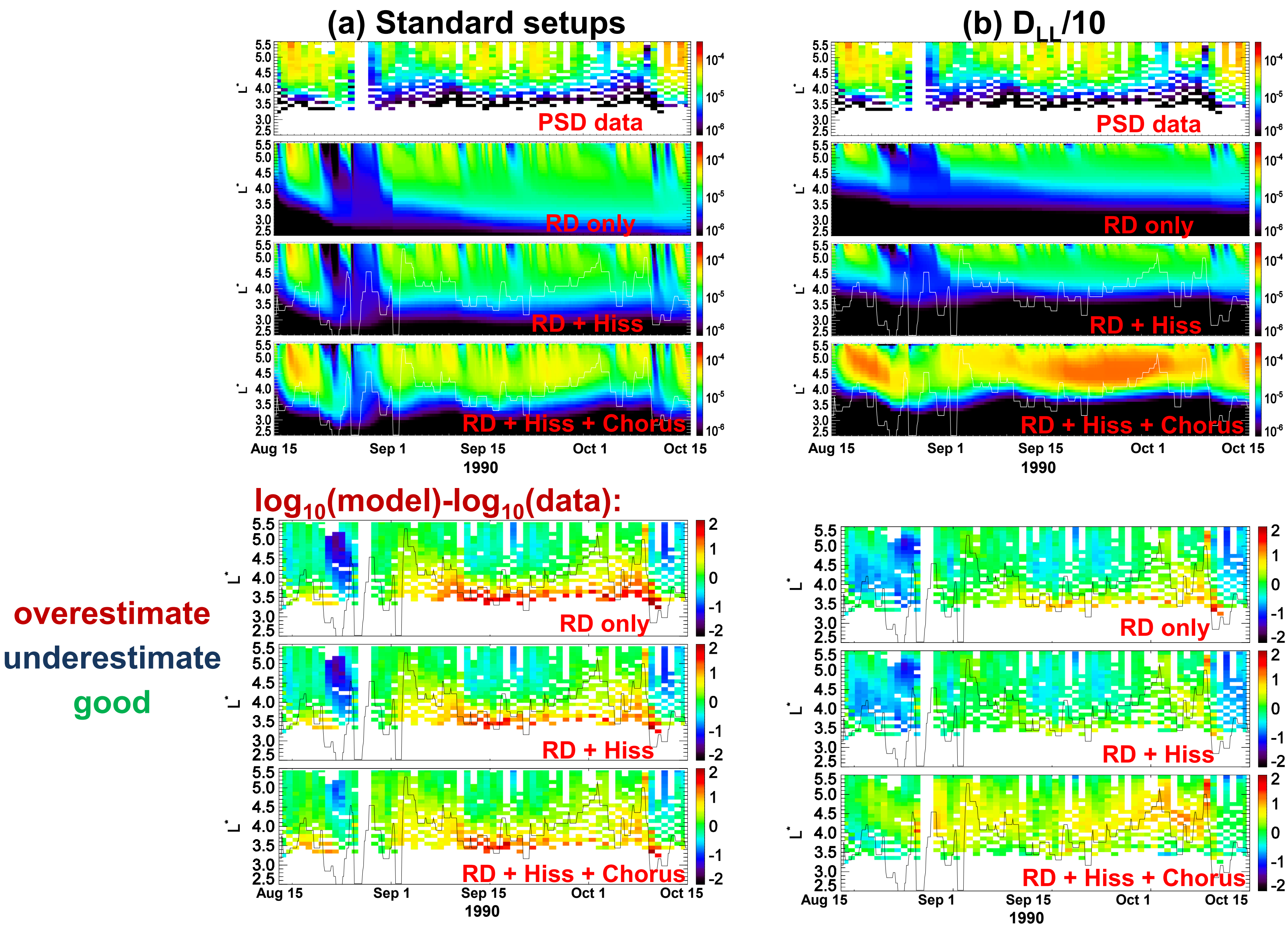
overestimate

underestimate

good

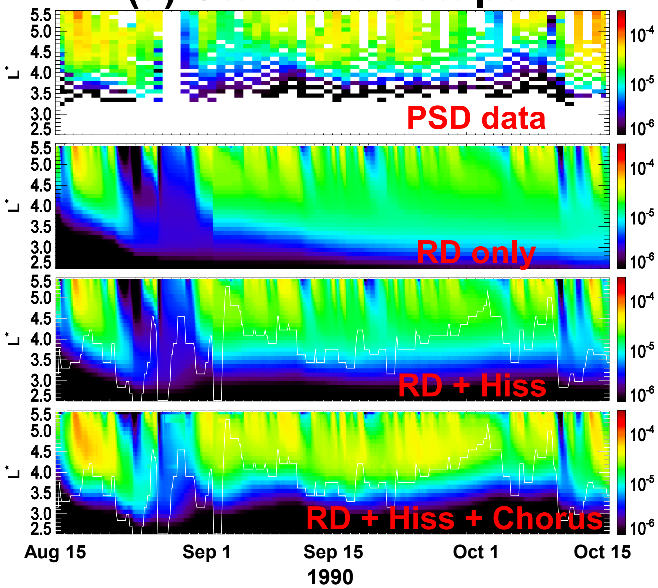


Model Results: GEM training interval

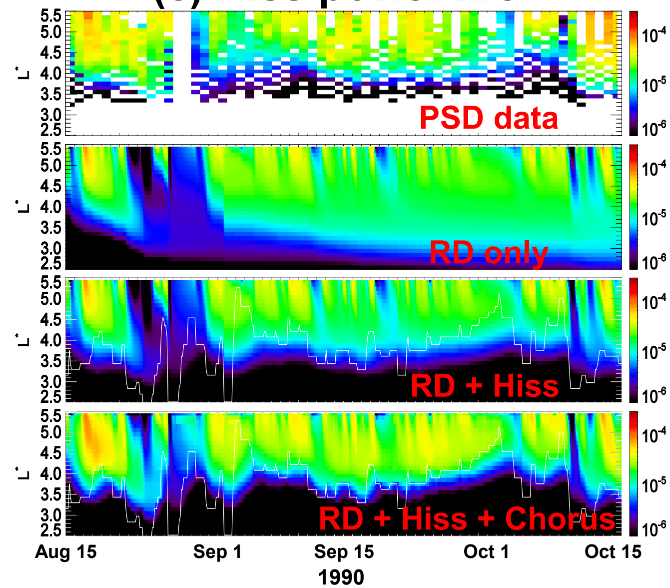


Model Results: GEM training interval

(a) Standard setups



(c) Hiss power X 5

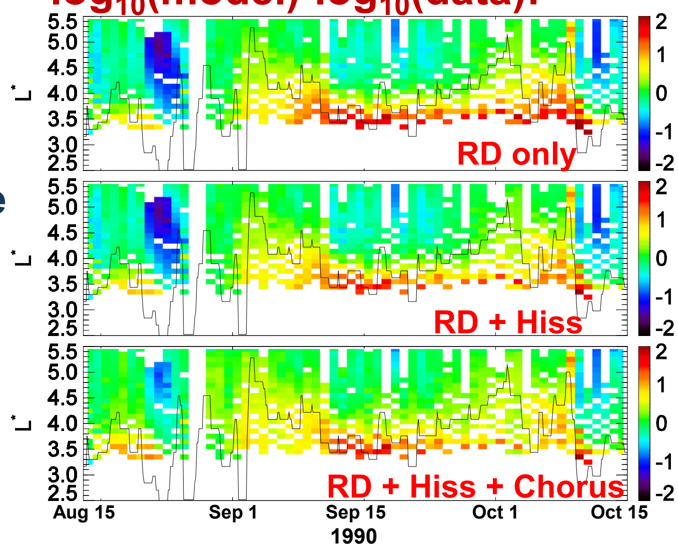


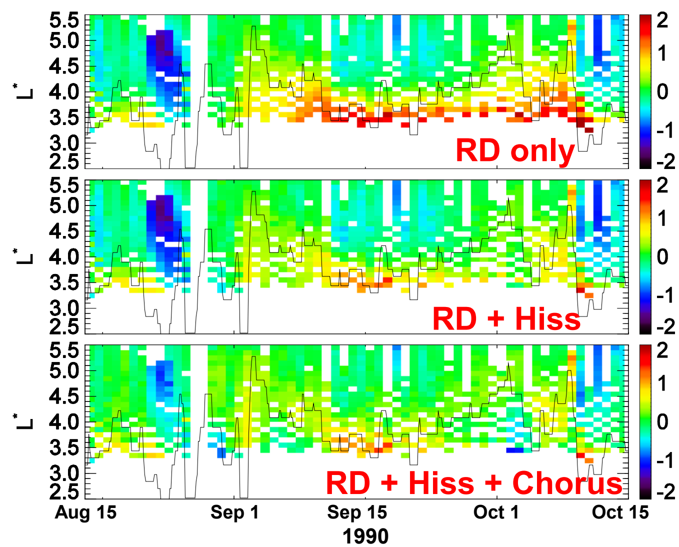
$\log_{10}$(model)-$\log_{10}$(data):

overestimate

underestimate

good





Model Results: GEM challenge interval

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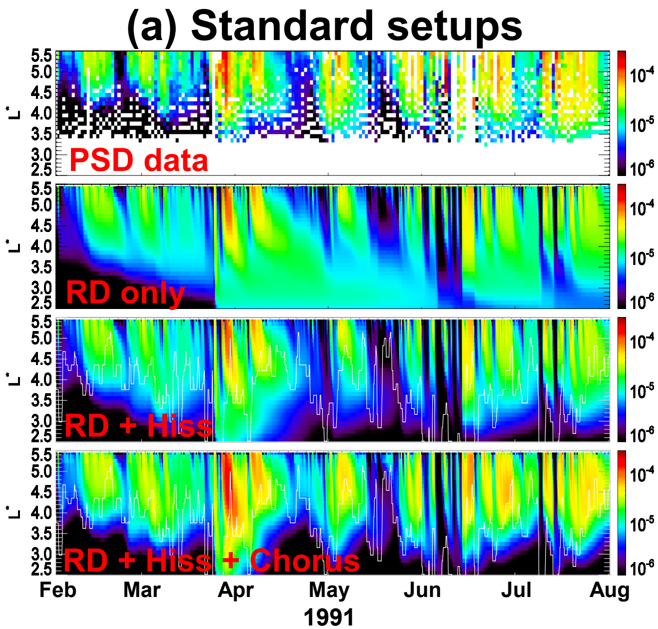
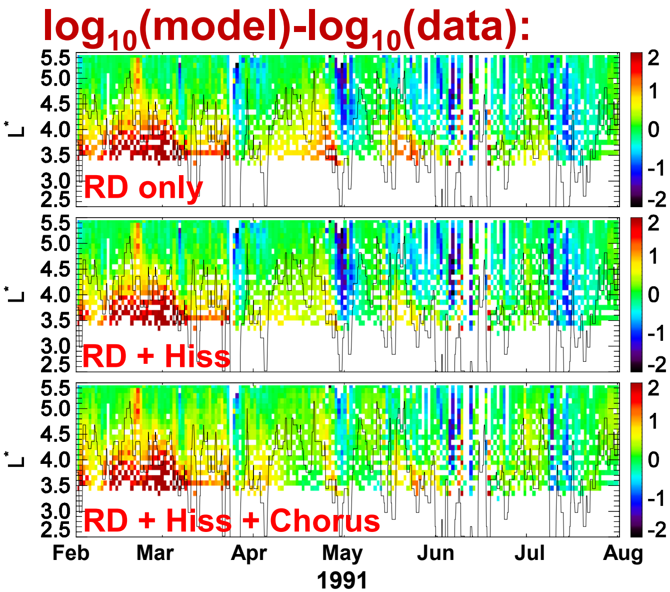


overestimate
underestimate
good



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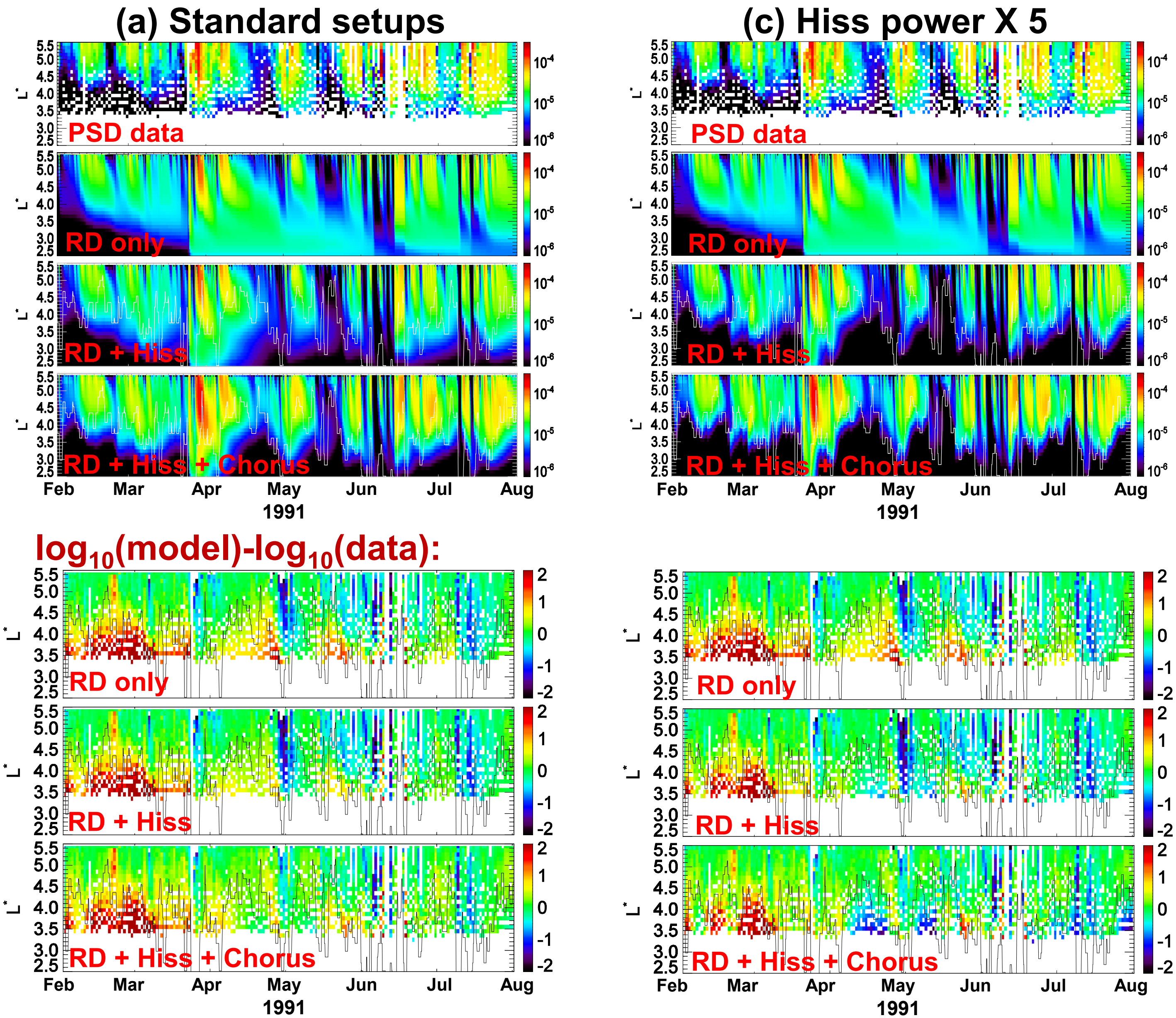

overestimate
underestimate
good

Quantitative Performance Metrics

- Mean Absolute Percentage Error [Kim et al., 2012]

$$\mathrm{MAPE}(\%)=\sum_{i=1}^{n}\left|\frac{\lg(m_i)-\lg(d_i)}{\lg(d_i)}\right|\times 100/n$$

d_i : data; m_i: model output

n: number of data points.

- Generally <30%, on average ~10% → the soundness of our model.

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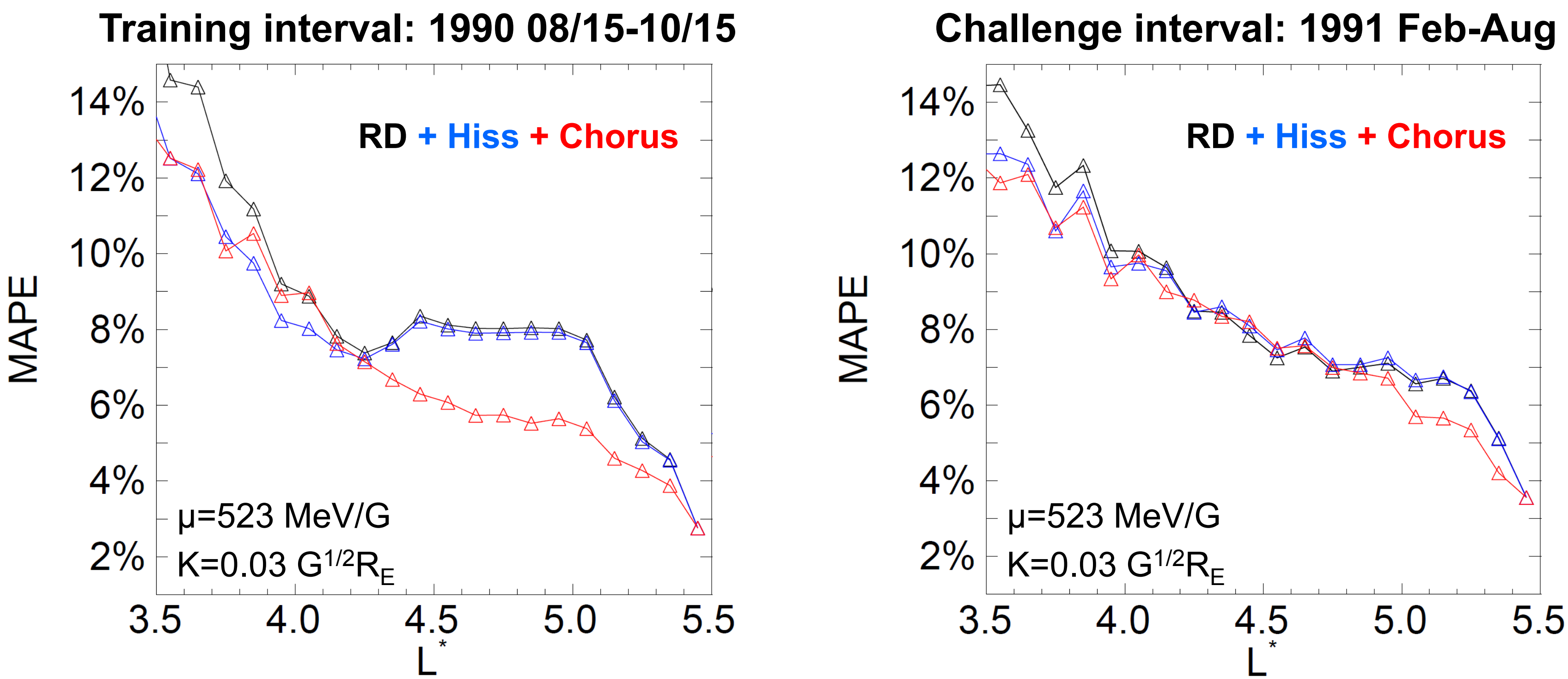
MAPE vs. L*



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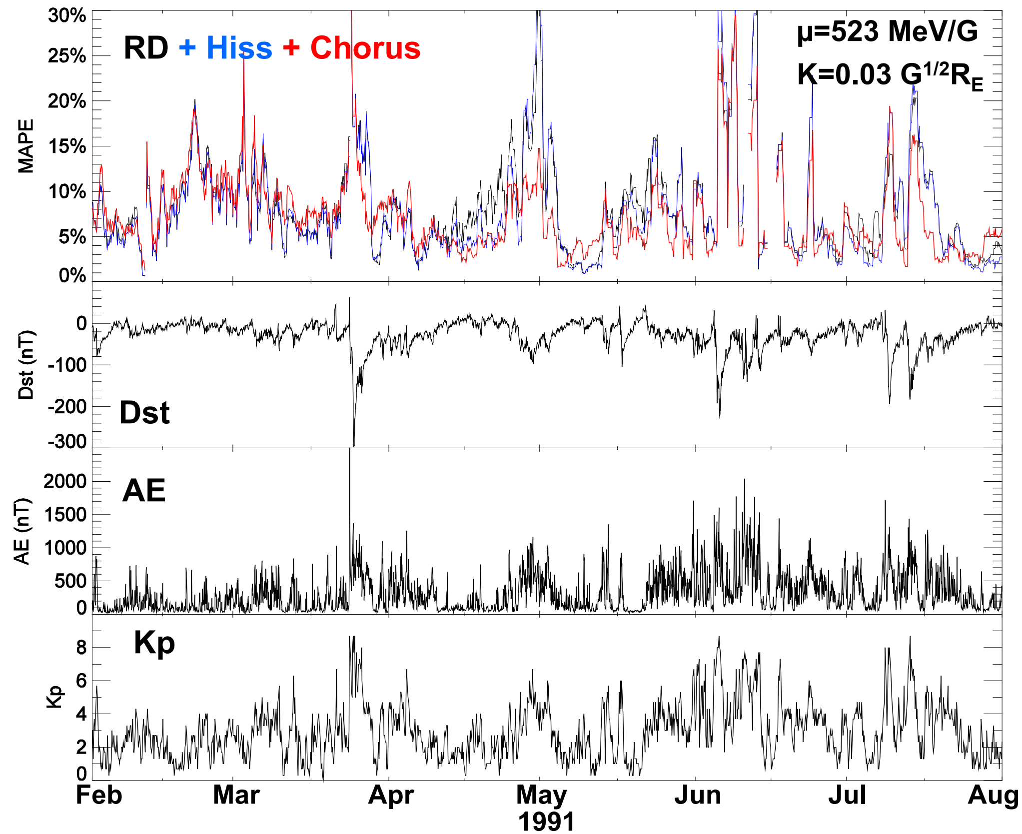
MAPE vs. time



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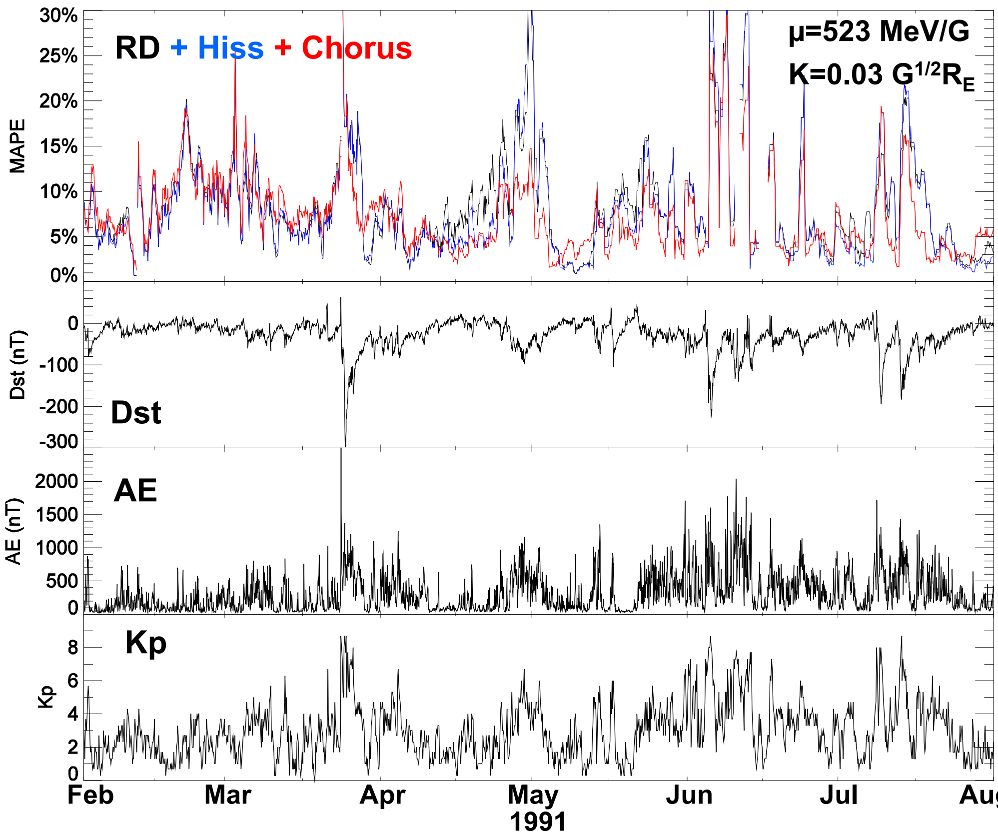
MAPE vs. activity

MAPE%	AE (nT)		
	<100	100–300	>300
RD only	7.33	7.62	10.40
RD+hiss	**6.43**	7.05	10.27
RD+hiss+chorus	6.98	**6.96**	**8.20**

Red cell: the lowest MAPE of all 3 runs.

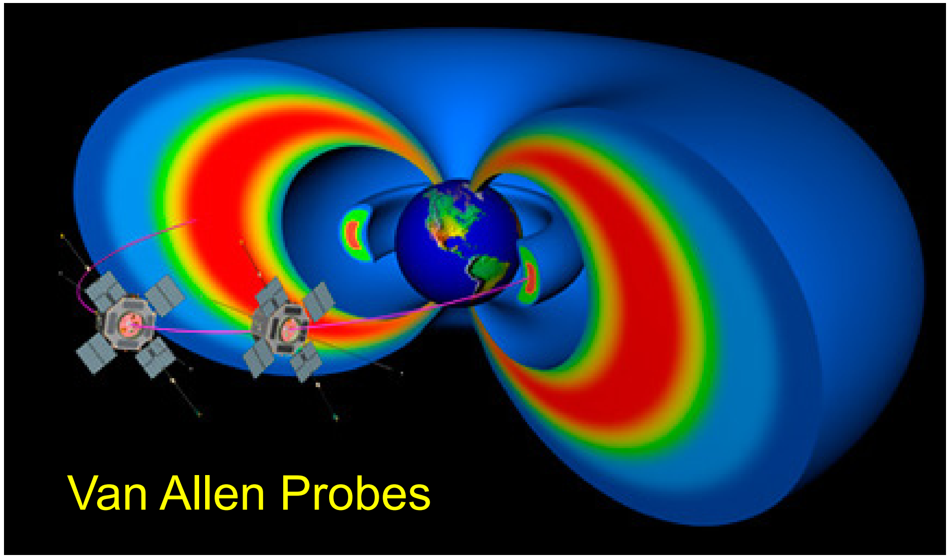
MAPE vs. time



Conclusions: Long-term simulation

- The simulation results from our 3D diffusion model on the CRRES era suggest:
  - Our model captures the general variations of radiation belt electrons, including the dropouts and the enhancements.
  - The overestimations inside the plasmapause can be improved by increasing the PA diffusion from hiss waves.
  - But to explain the details dynamics, better D_{LL} and wave models are required.

Part 2: Simulation of the October 2012 Van Allen Probes event



- Event-specific model inputs and boundary conditions driven by measurements from Van Allen Probes and other spacecraft
- Published in Tu et al. [GRL 2014]

DREAM3D Diffusion Model

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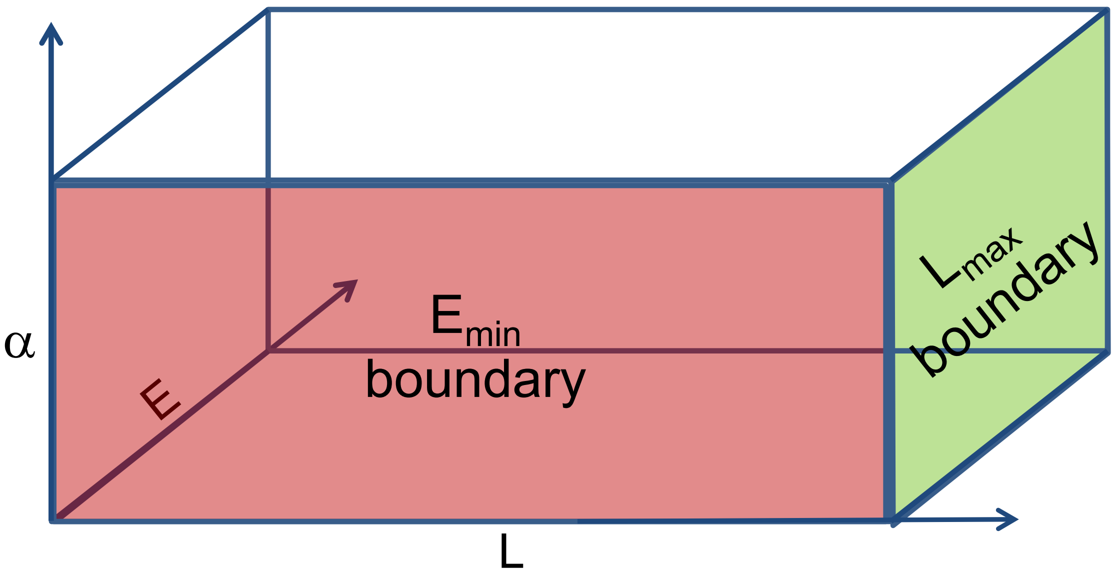
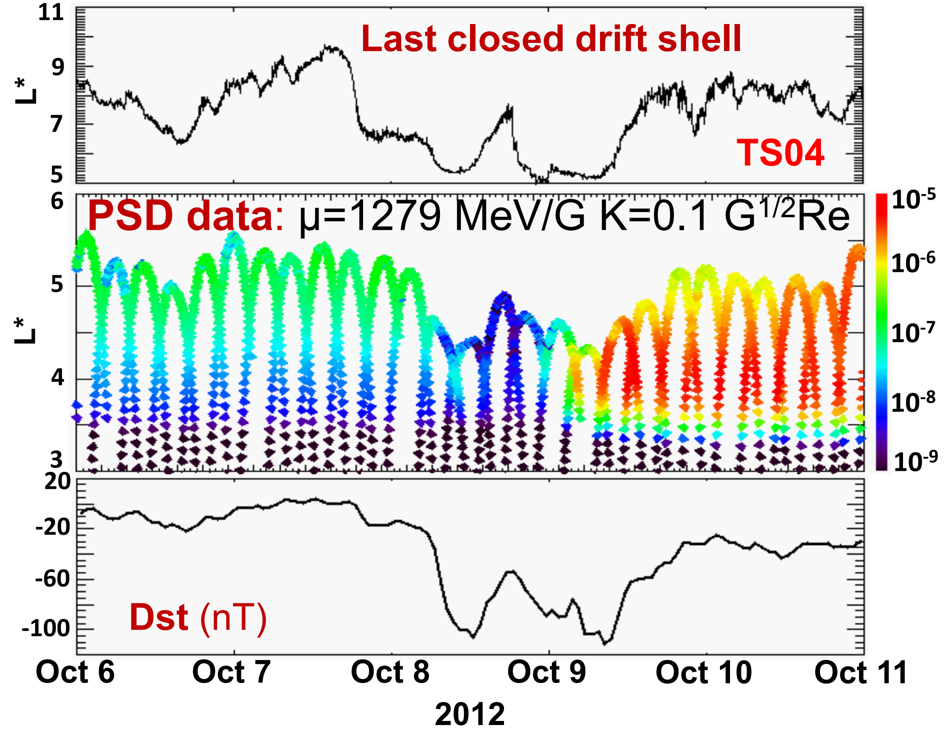


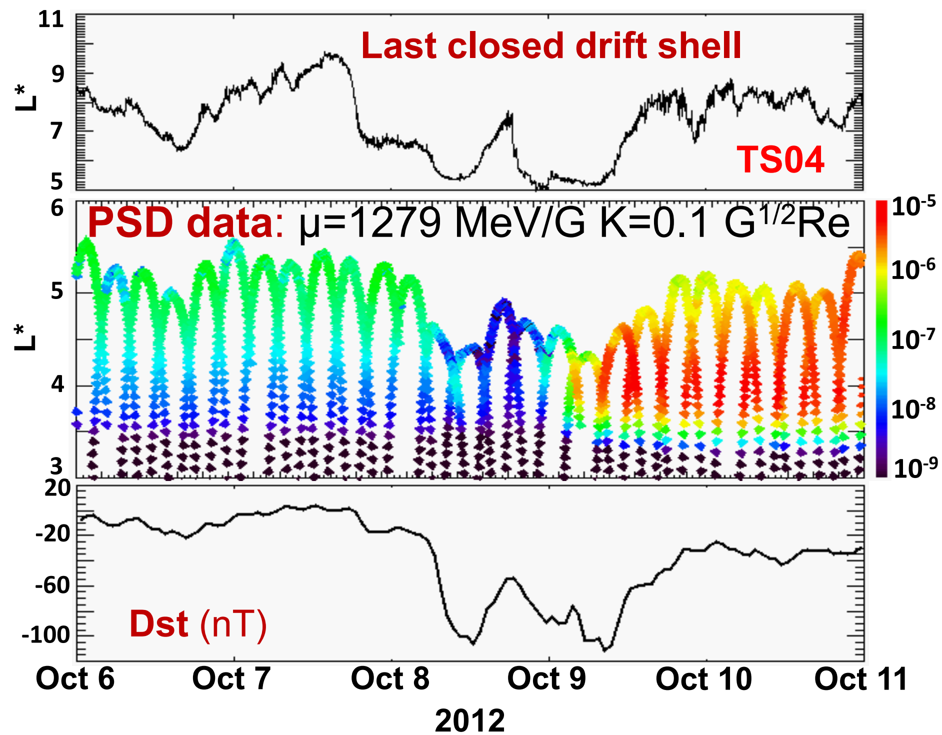
Van Allen Probes event: October 2012

- Fast dropout
- Strong enhancement:
  - Reported by Reeves et al. [Science, 2013]



DREAM3D simulation: RB dropout

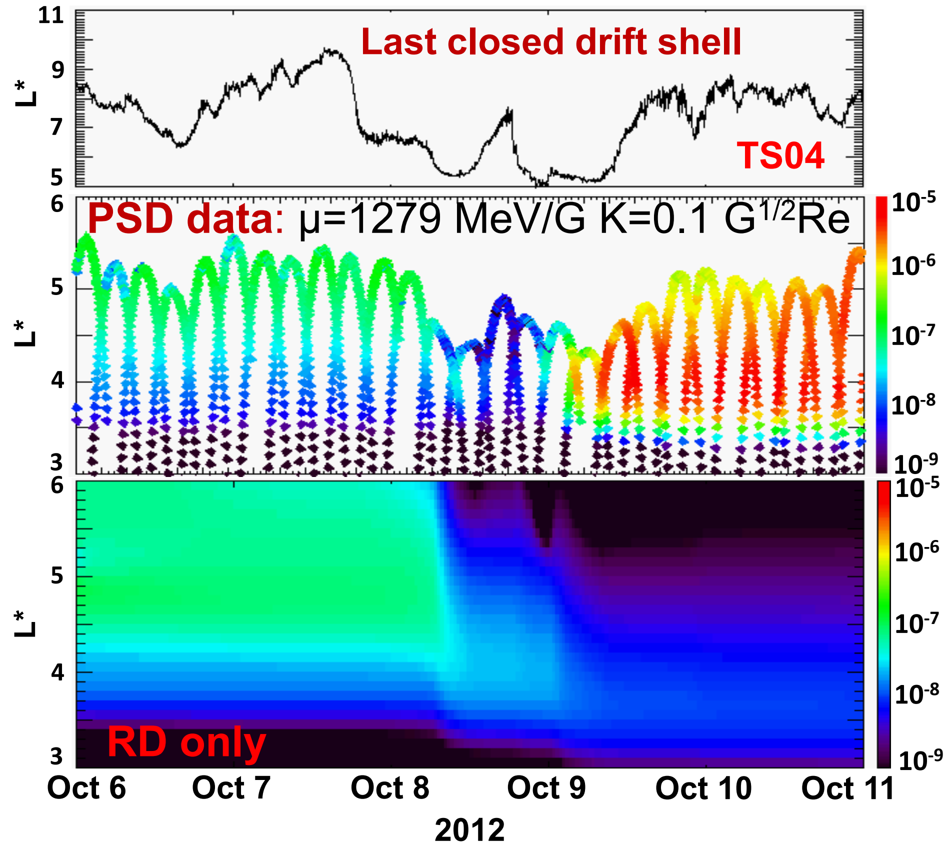
- 'Open' boundary at L_{max}=11
- Short lifetimes (E-dependent) outside LCDS



DREAM3D simulation: RB dropout

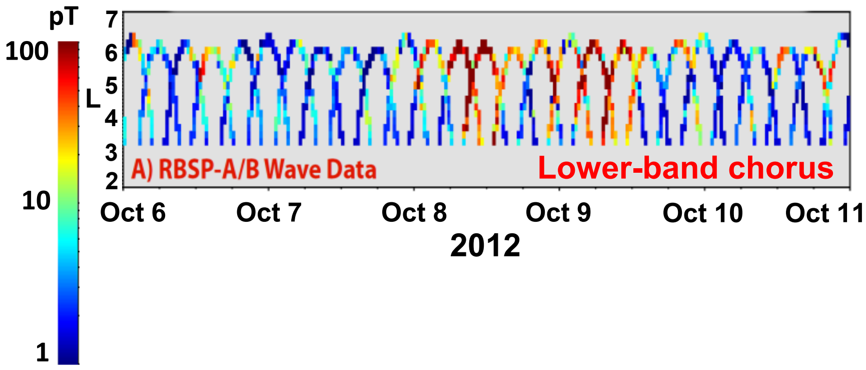
- ‘Open’ boundary at L_{max}=11
- Short lifetimes (E-dependent) outside LCDS

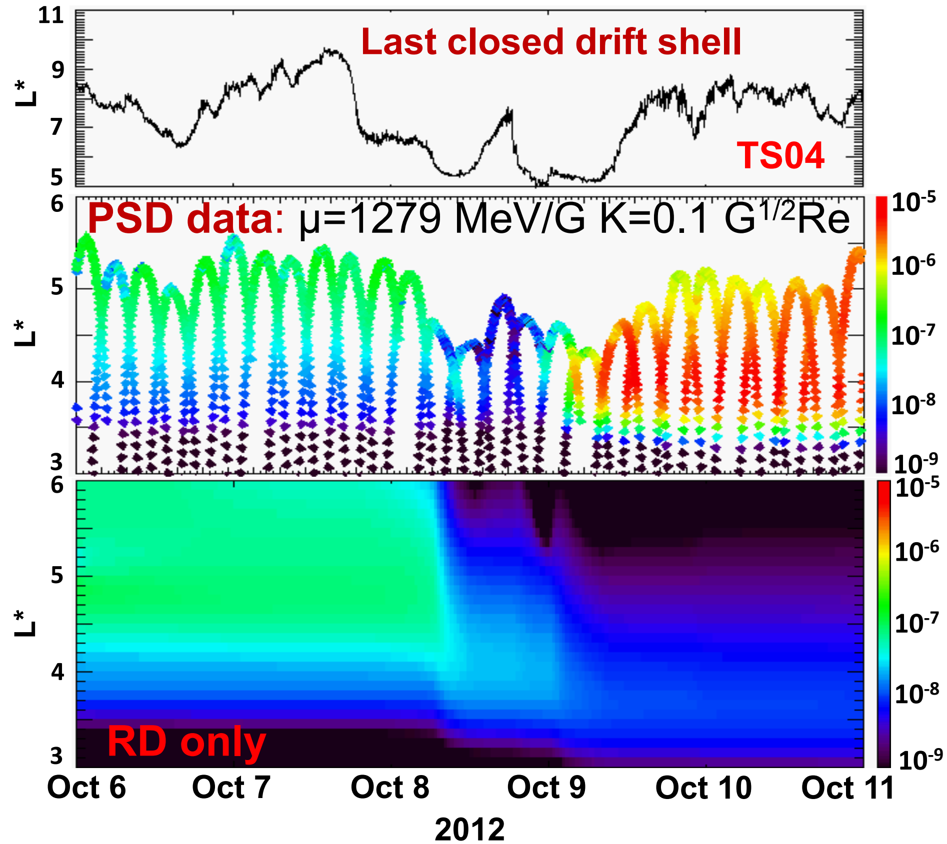
➢ RB dropout reproduced by magnetopause shadowing + outward radial diffusion



DREAM3D simulation: RB enhancement

Event-specific chorus wave model





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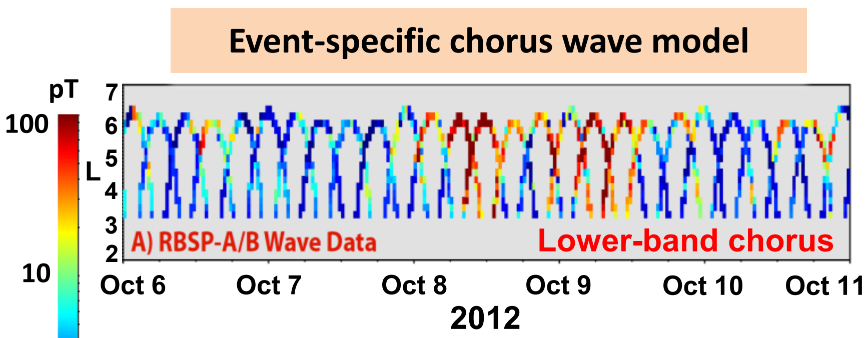

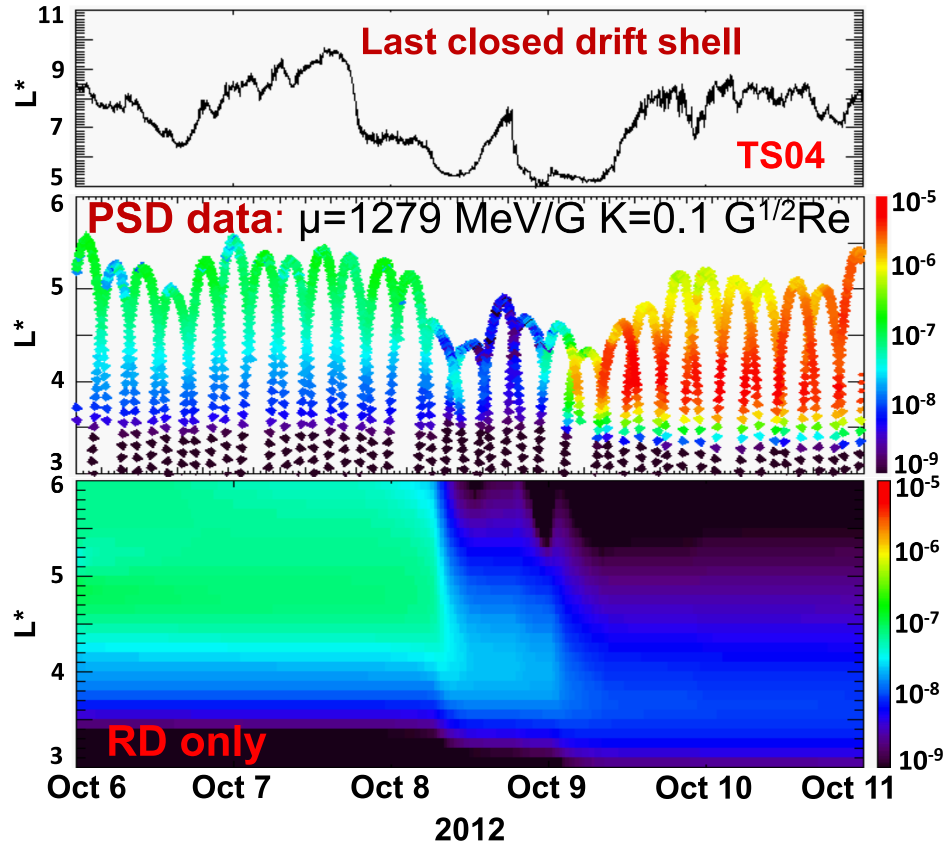

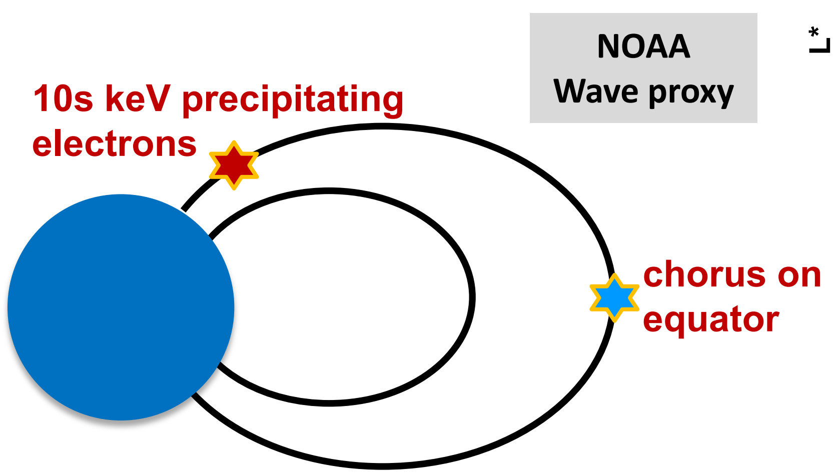

DREAM3D simulation: RB enhancement

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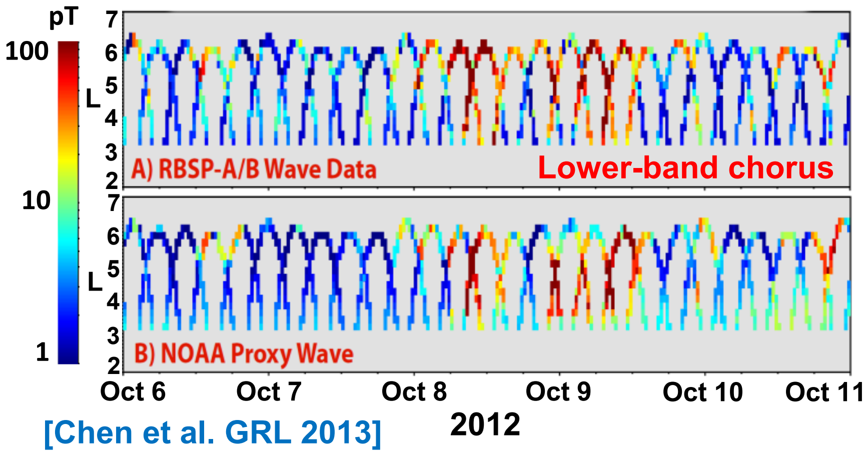
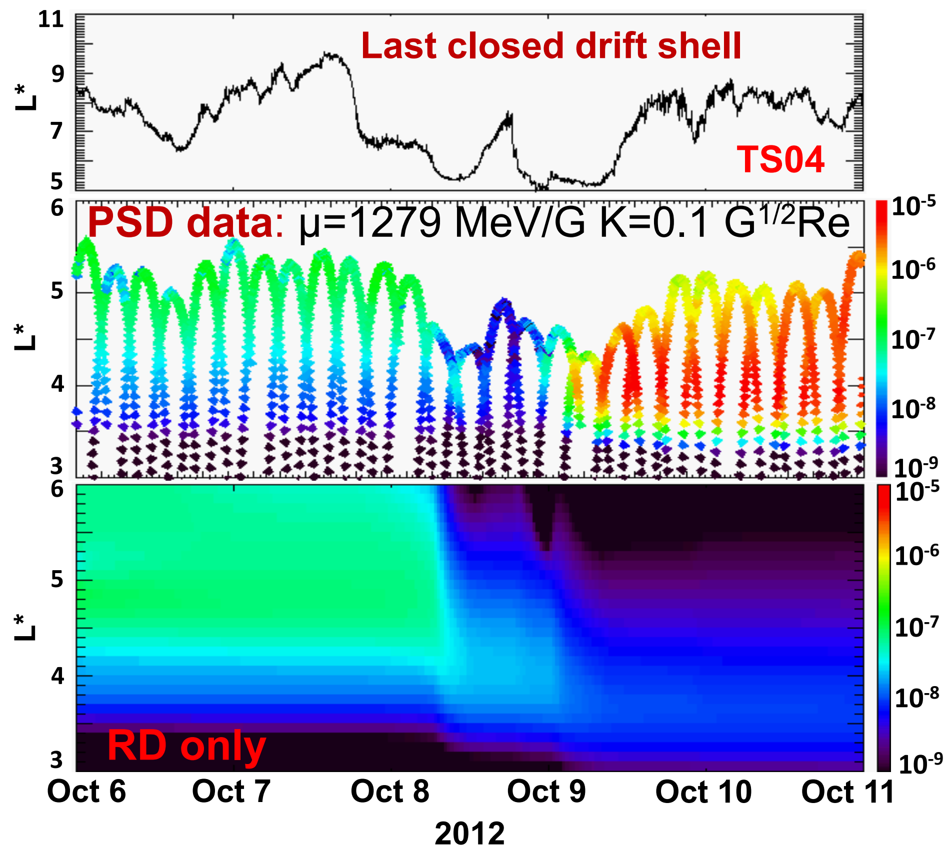
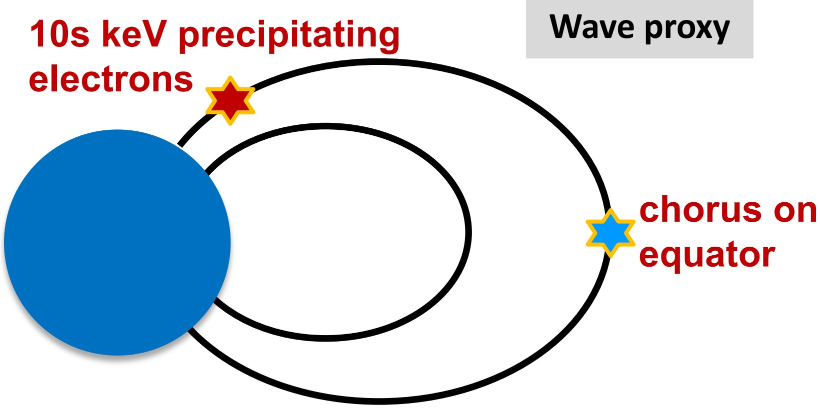


[Chen et al. GRL 2013]

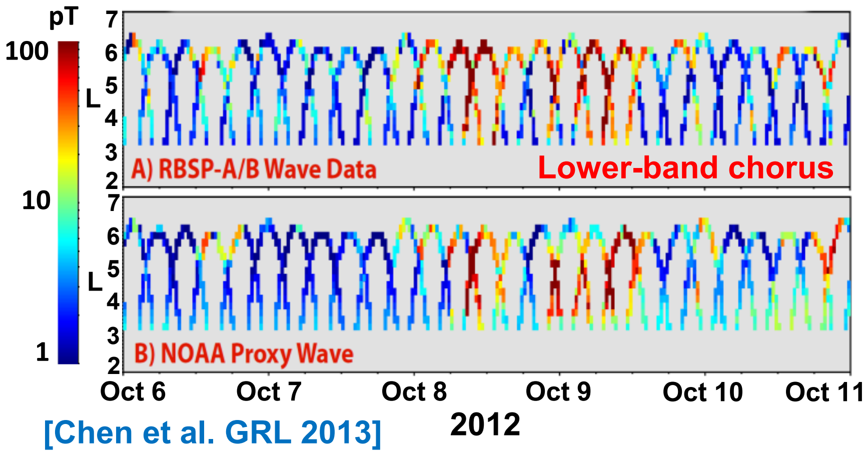


NOAA
Wave proxy



DREAM3D simulation: RB enhancement

Event-specific chorus wave model



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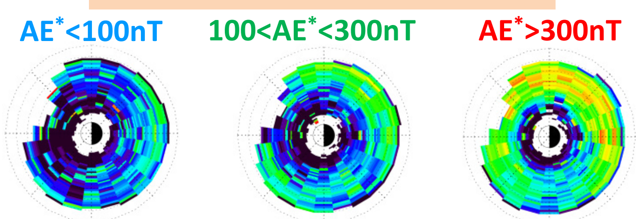
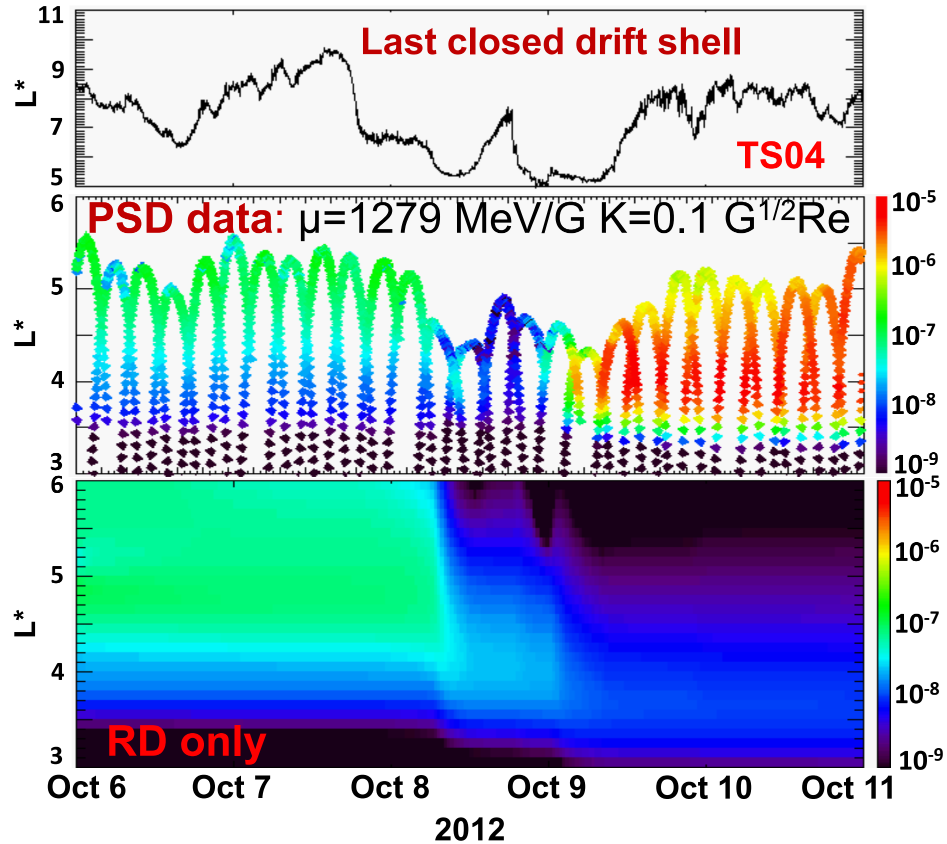
CRRES-based Statistical model



[Tu et al. JGR 2013]



DREAM3D simulation: RB enhancement

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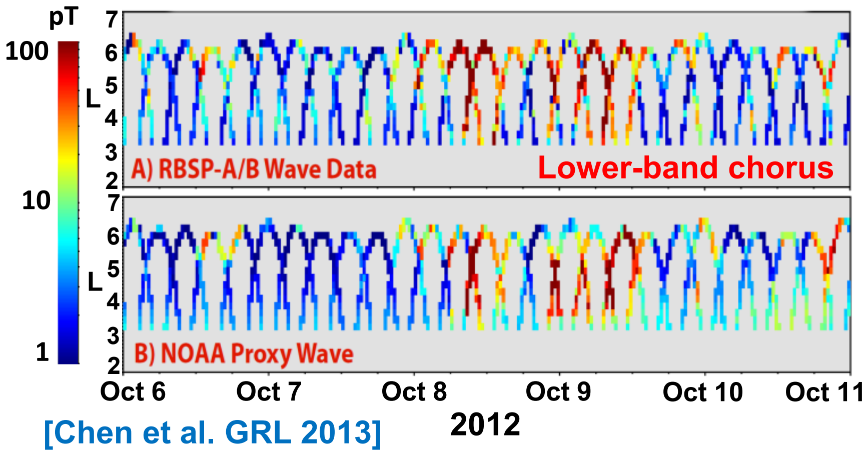
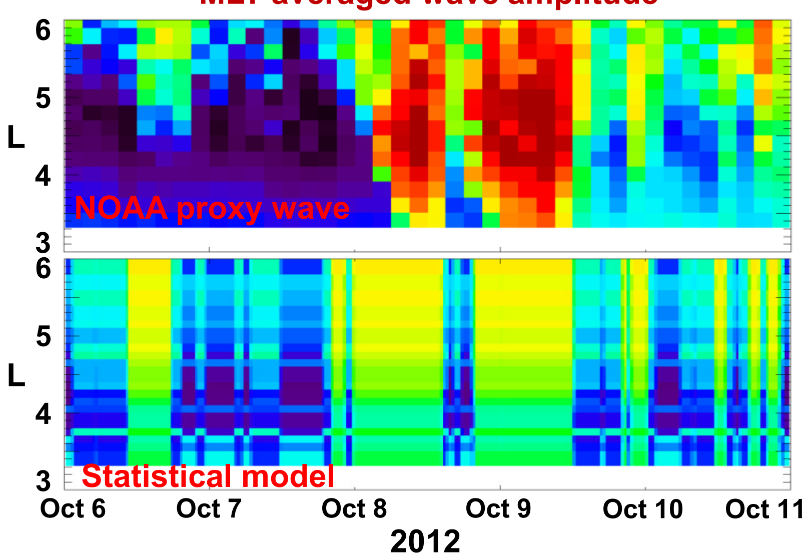
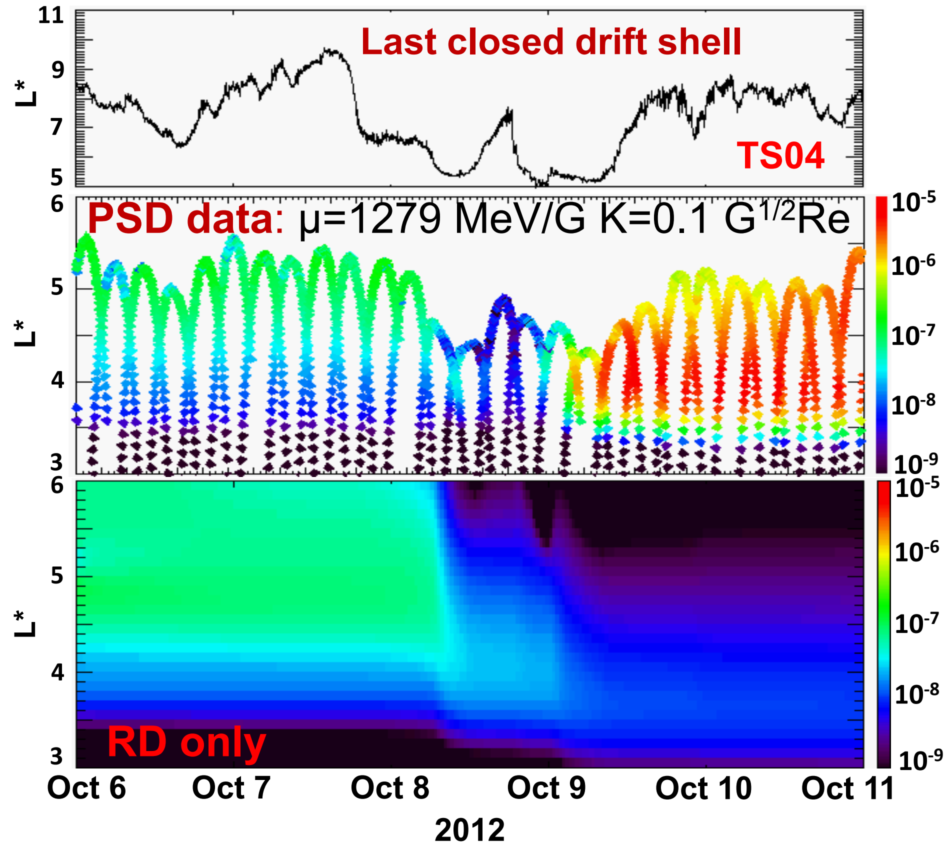


[Chen et al. GRL 2013]

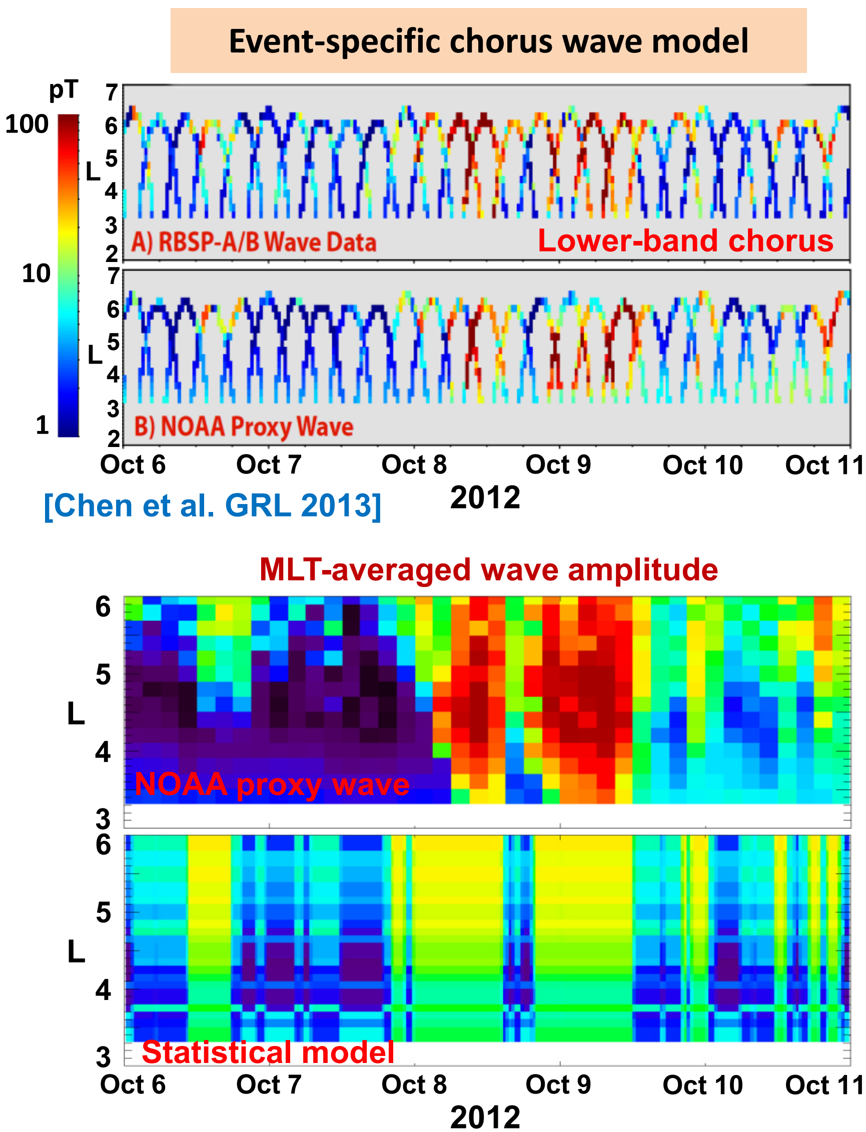
MLT-averaged wave amplitude

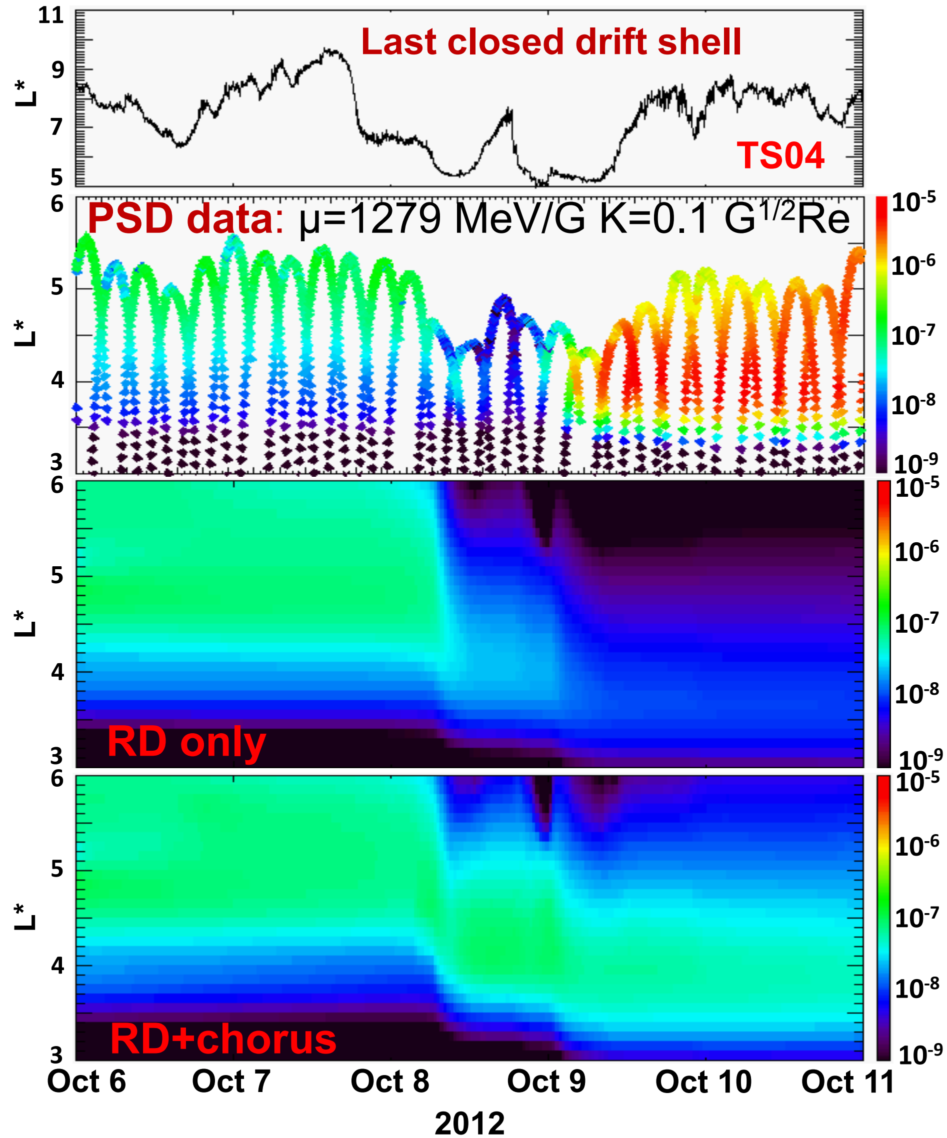




- wave amplitude: **10x higher** than the statistical model
- Energy diffusion: **100x faster**

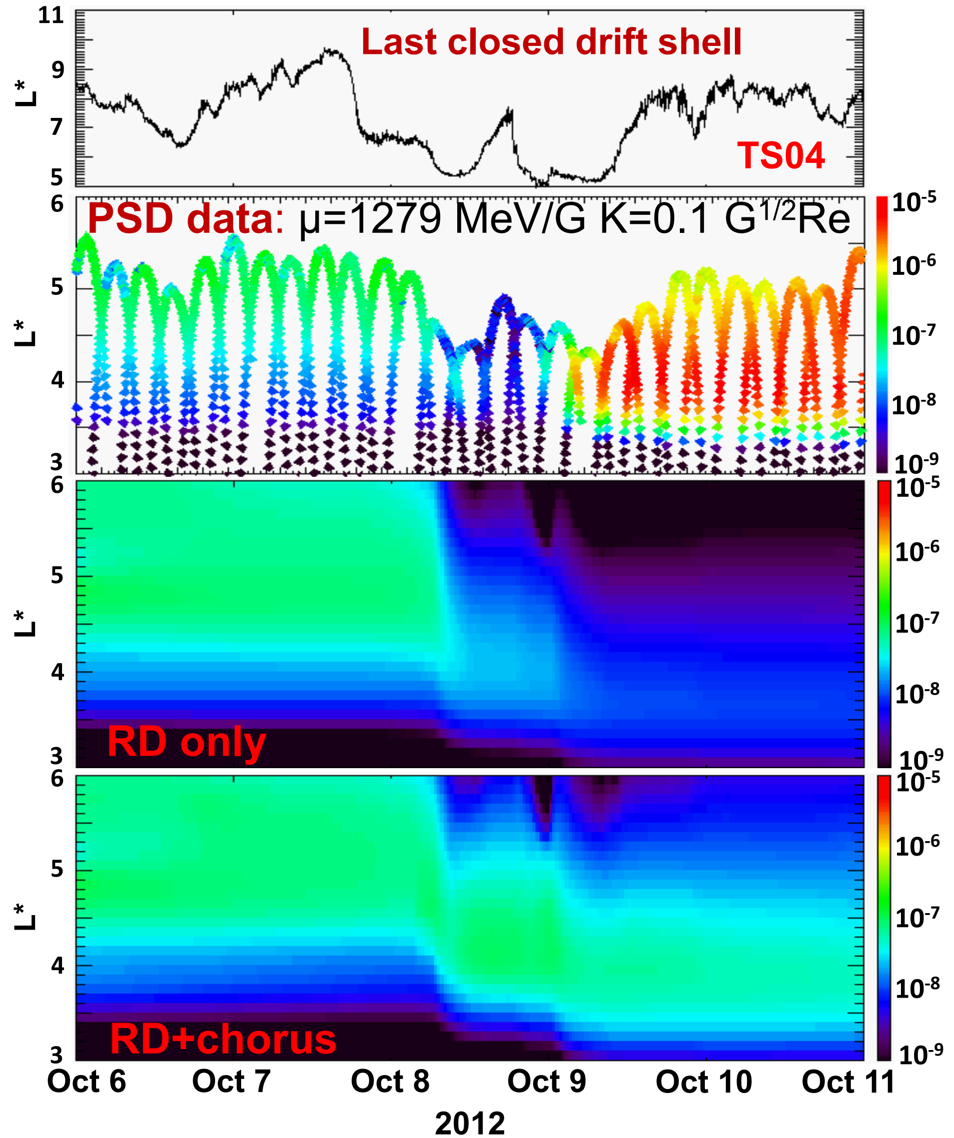
DREAM3D simulation: RB enhancement





DREAM3D simulation: RB enhancement

- Modeling the enhancement
  - Event-specific chorus waves
  - Realistic seed electrons (100 keV)



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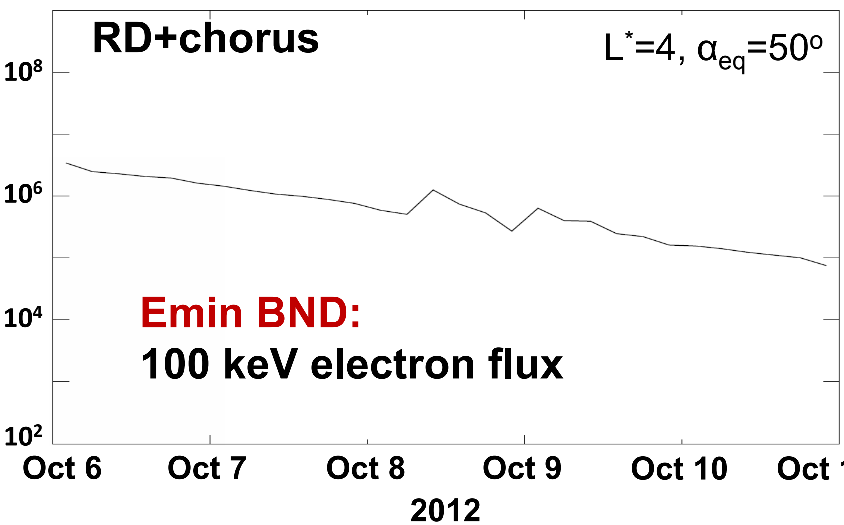
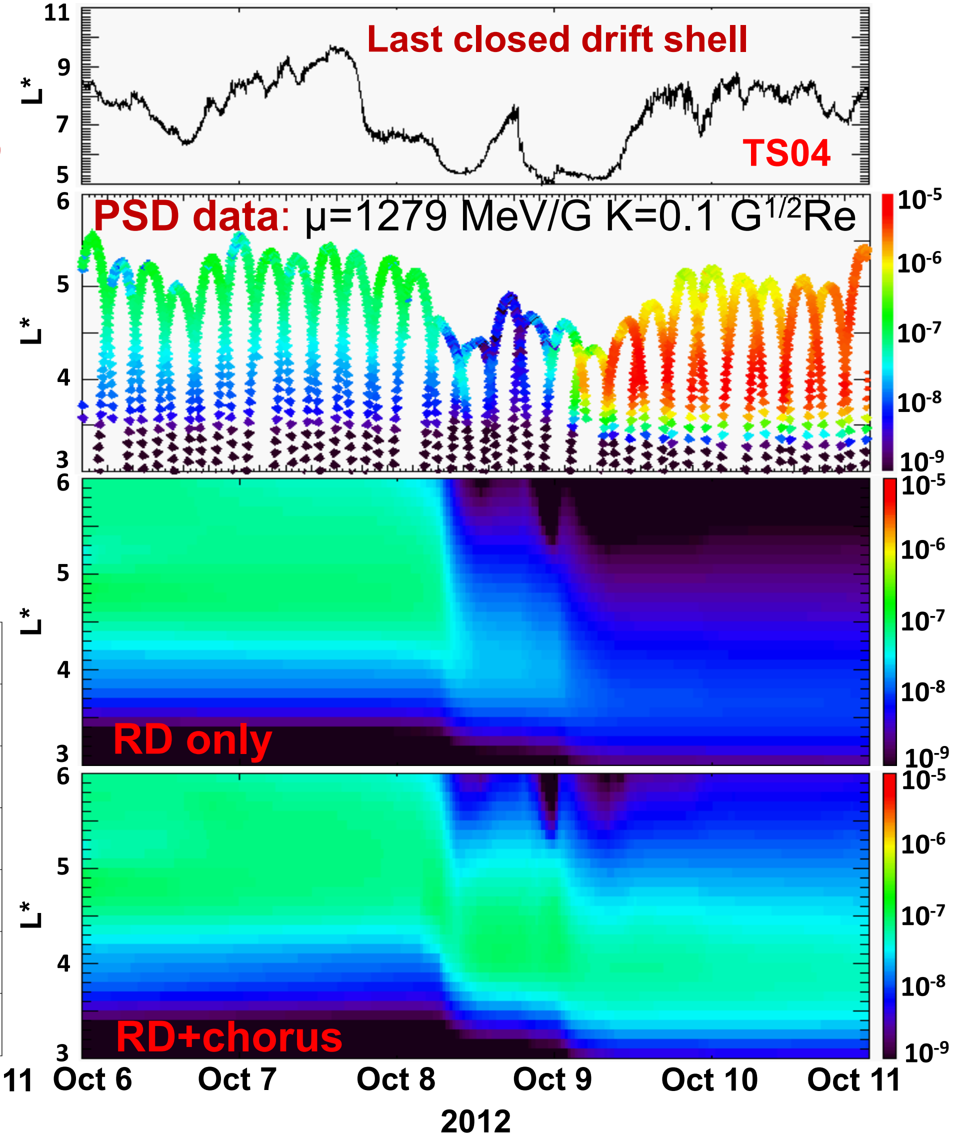
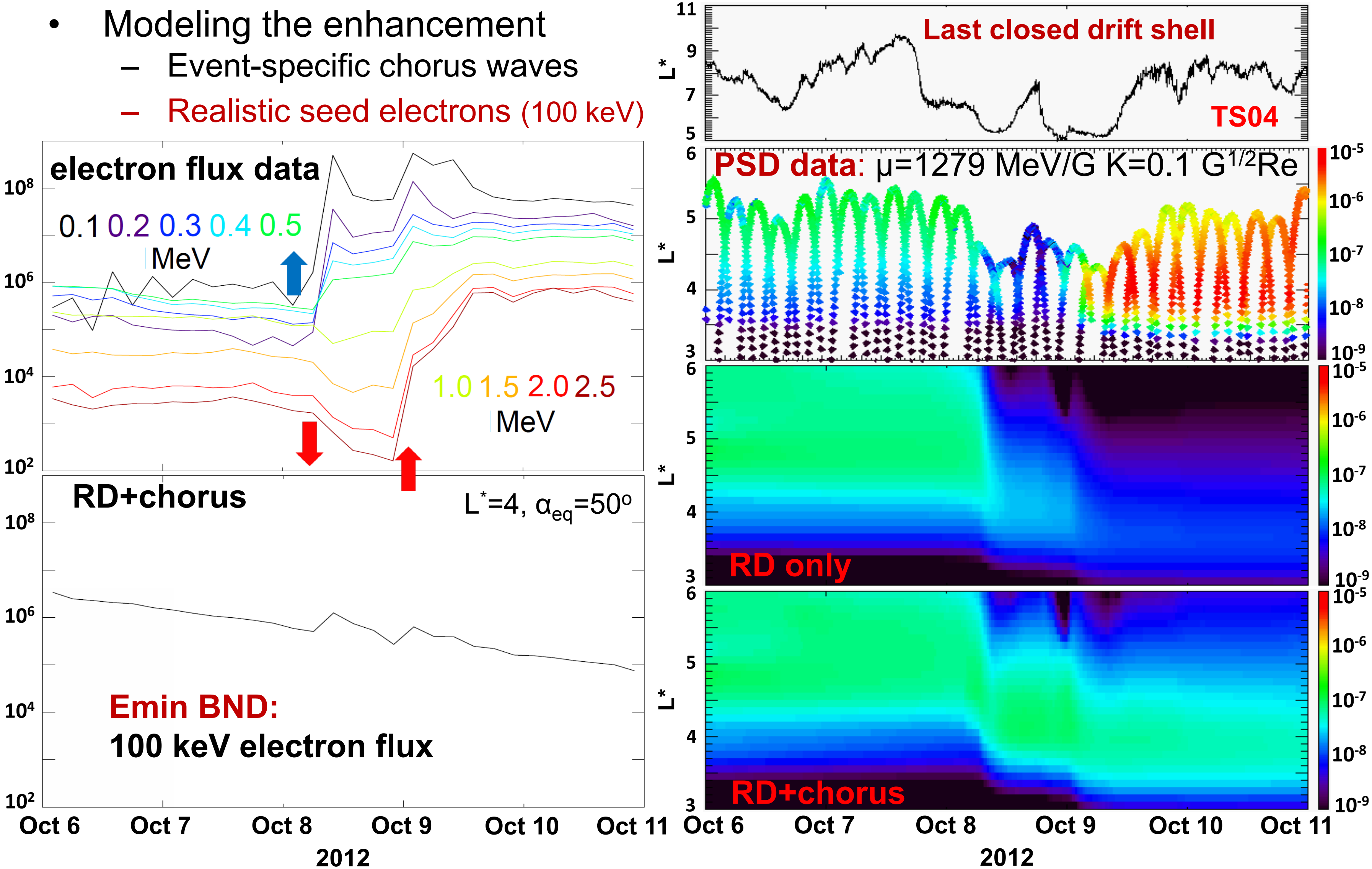




DREAM3D simulation: RB enhancement

- Modeling the enhancement
  - Event-specific chorus waves
  - Realistic seed electrons (100 keV)



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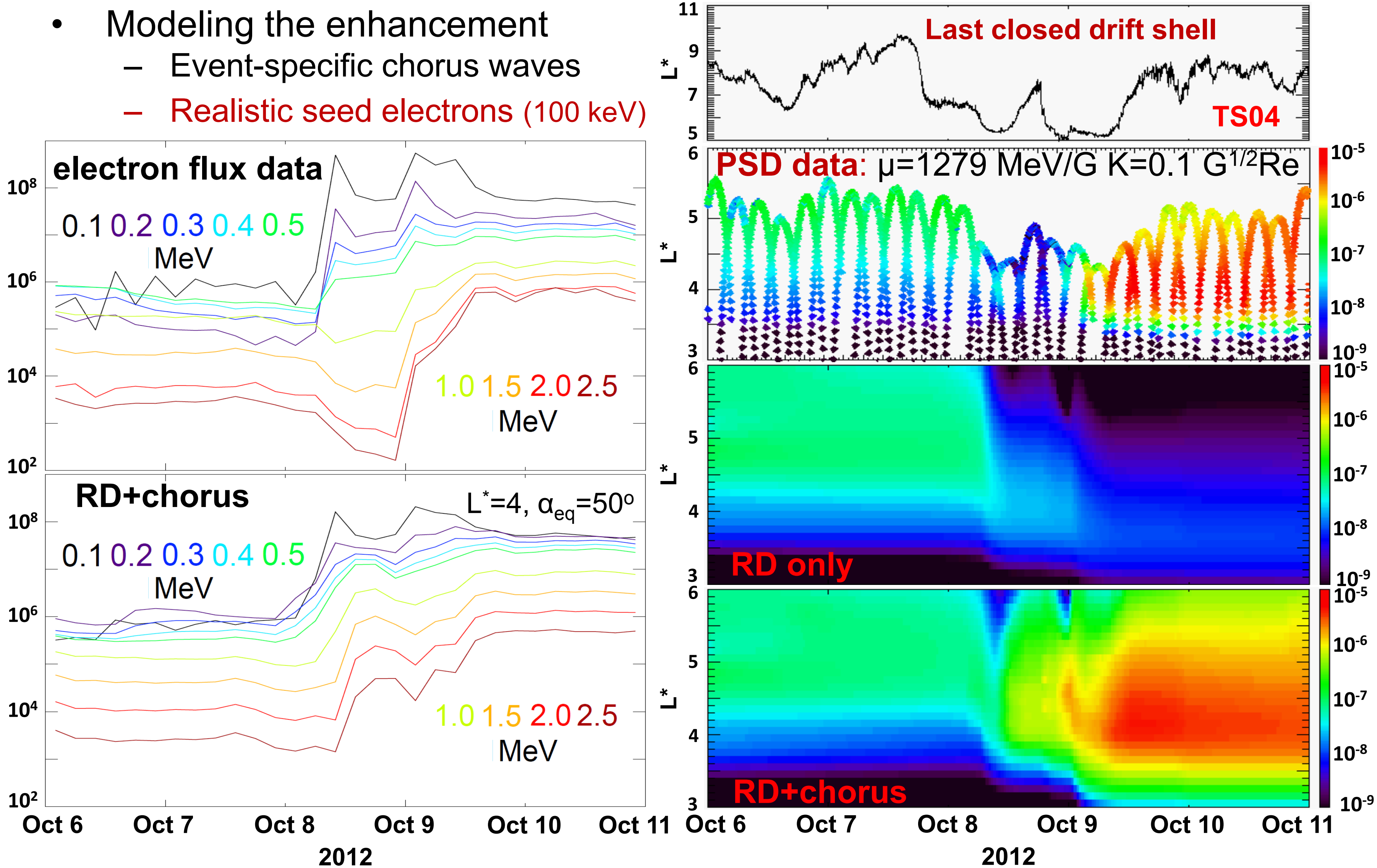
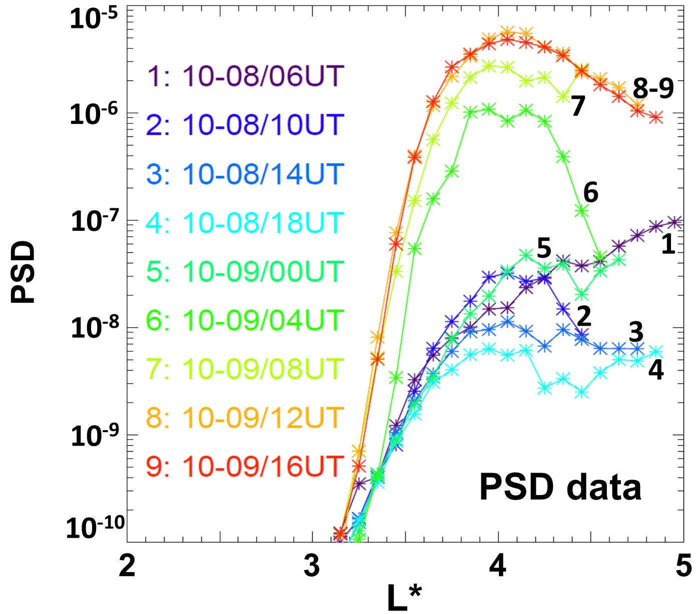
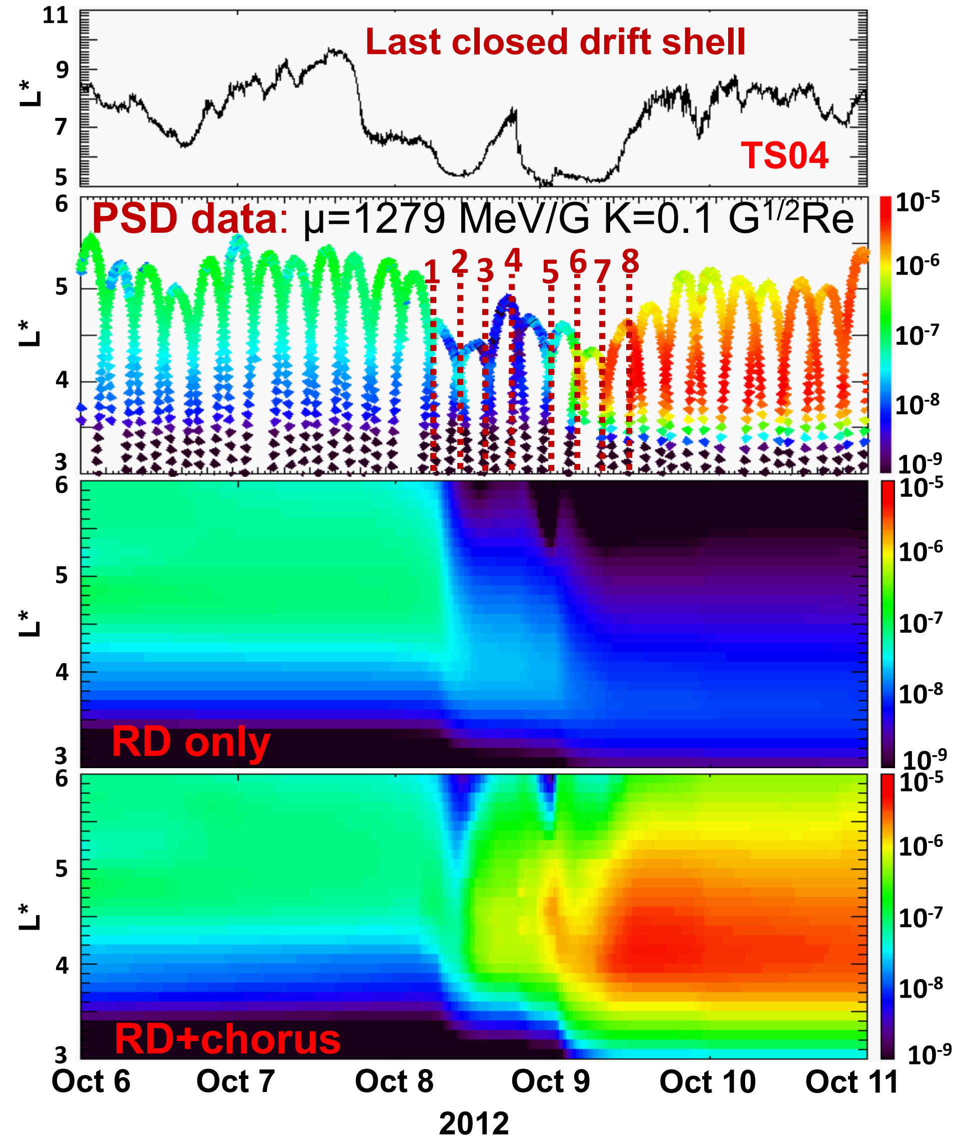


Detail comparison: PSD vs. L profile





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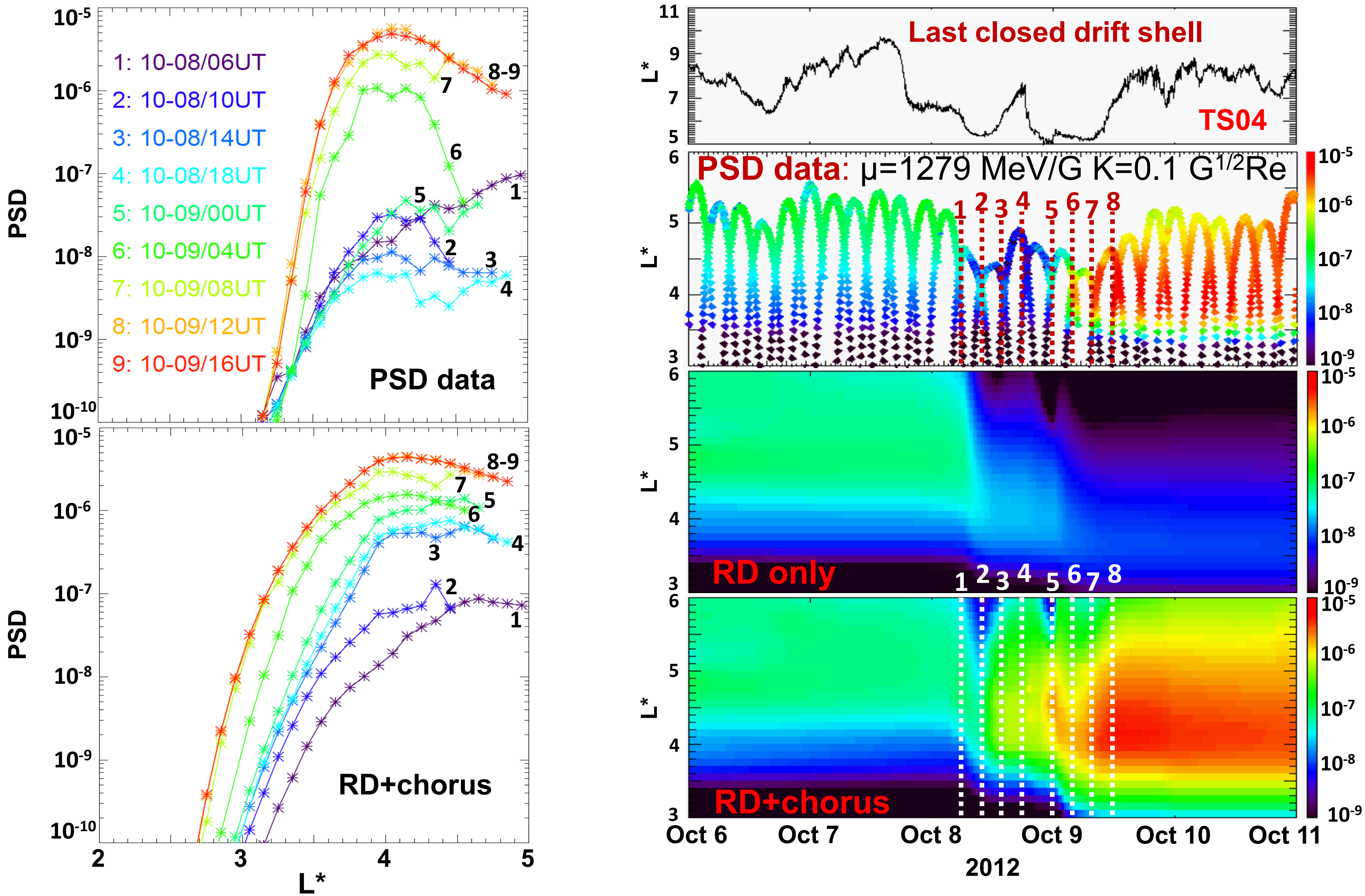

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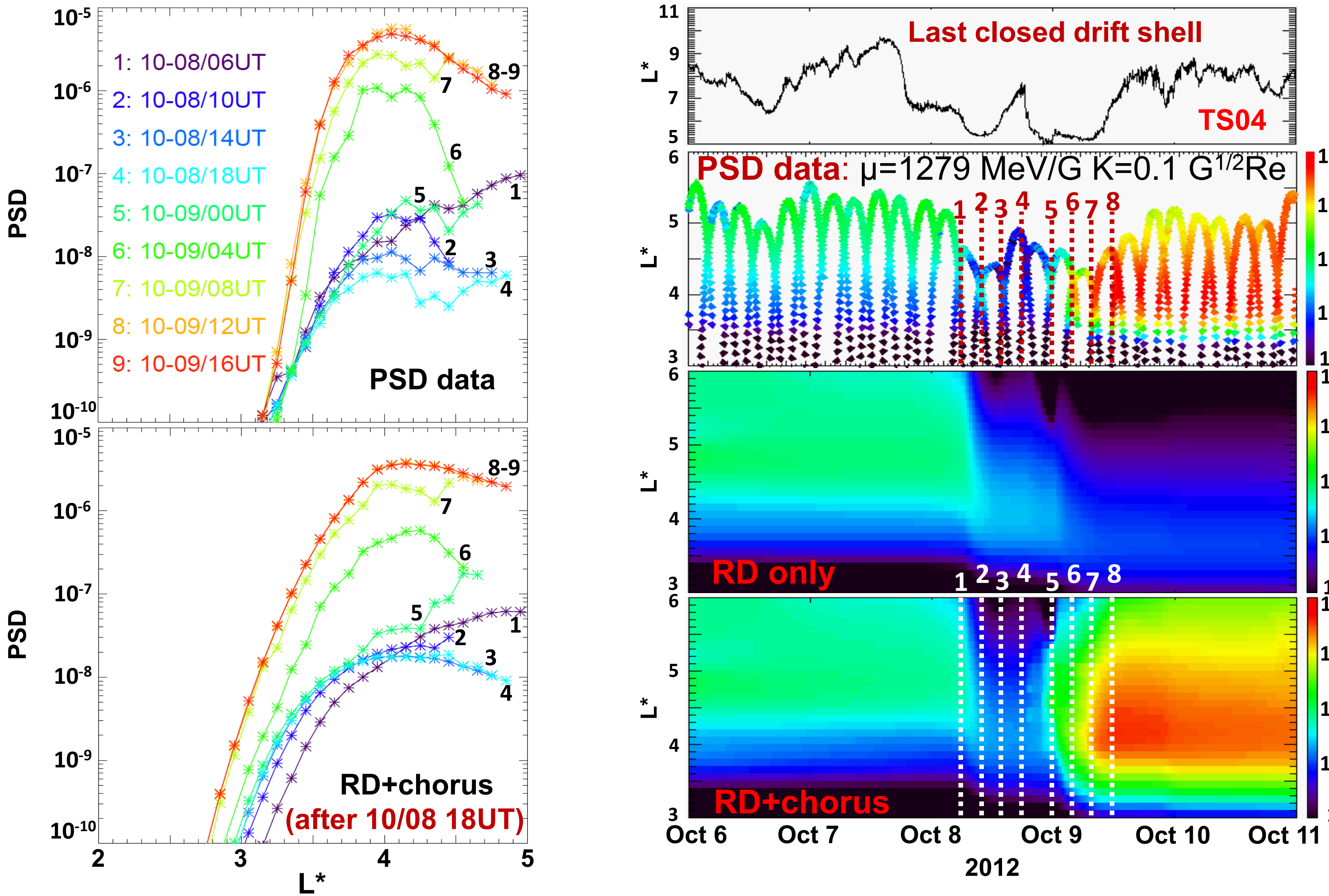

Conclusions: Event simulation

- To simulate the October 2012 event, three new modifications to DREAM3D have been implemented, all driven by event-specific conditions:
  - Solar-wind driven last closed drift shell: OMNI data
  - Event-specific chorus wave model: NOAA/POES, Van Allen Probes/EMFISIS
  - Data-driven electron seed population: Van Allen Probes/MagEIS
- Electron dropout during the 1st Dst dip can be explained by outward radial diffusion to the compressed last closed drift shell.
  - Though it is not well-reproduced if chorus heating is turned on simultaneously.
- Strong enhancement during the 2nd Dst dip is well reproduced with event-specific chorus waves and electron seed population.
- The results illustrate the utility of the high-resolution, comprehensive set of Van Allen Probes measurements in studying the balance between source and loss in the radiation belt.

New GEM Focus Group (2014-2018):

- A new GEM/FG on "Quantitative Assessment of Radiation Belt Modeling" under the IMS Research Area.
- Co-chairs: Weichao Tu, Wen Li, Jay Albert, Steve Morley
- Goals:
  - Bring together the current state-of-the-art models and new physics for the acceleration, transport, and loss processes in radiation belts.
  - Develop event-specific and global wave, plasma, and magnetic field models to drive these radiation belt models.
  - Combine all these components to achieve a quantitative assessment of the relative importance of acceleration, transport, and loss processes in radiation belts by validating against contemporary radiation belt measurements.
- 'RB dropout' and 'RB buildup' challenges invite international participations!