Forecasting and Remote Sensing Relativistic Electron Dynamics from Low-Earth-Orbits

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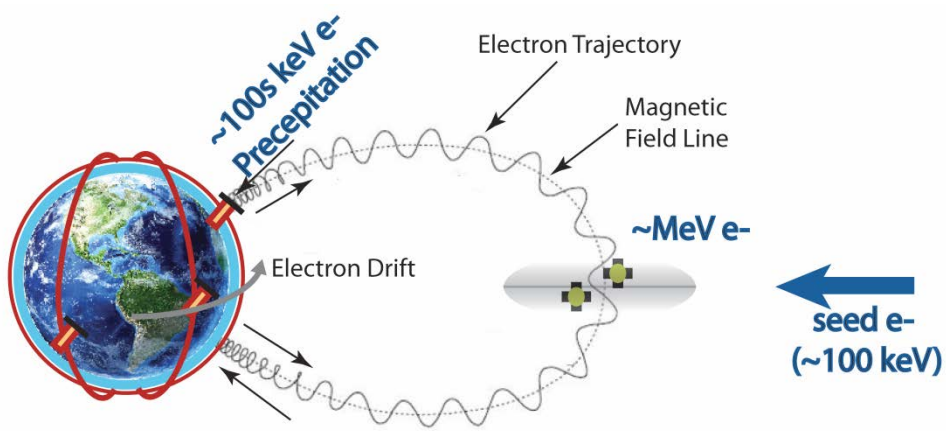

- Existence of a cross-energy, cross-pitch-angle coherence between trapped MeV electrons and precipitating low-energy electrons.
- A linear prediction filter, driven by LEO (POES) observations can reliably predict MeV electron population.
- This cross-energy coherence can be explained by classic wave-particle interaction picture.

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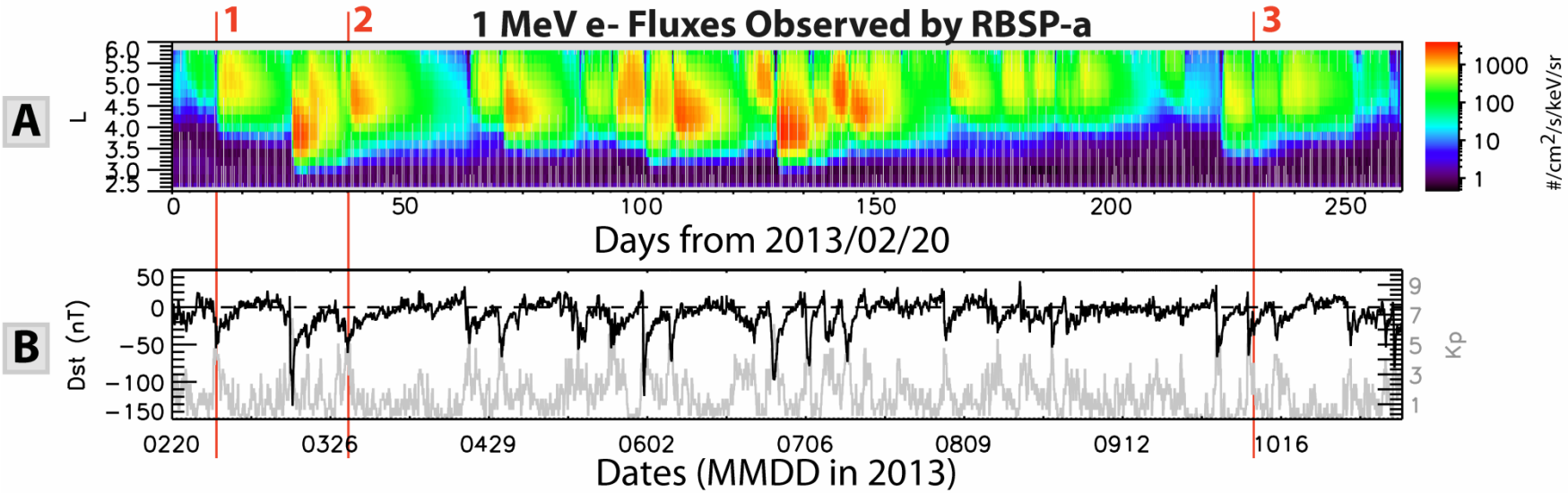
1. Background: Motivation

- Relativistic (MeV) electrons in the outer belt exhibit complicated, event-specific behaviors [e.g., *Reeves et al*., 2003; *Chen et al*., 2007].



- Reliable prediction of these event-specific behaviors of relativistic electrons has been a long-pursued and however is unfortunately still beyond our reach.

- This work aims to address the issue from a new perspective: **With inputs from existing LEO space infrastructure, we can have the invaluable predictive capability with high fidelity.**

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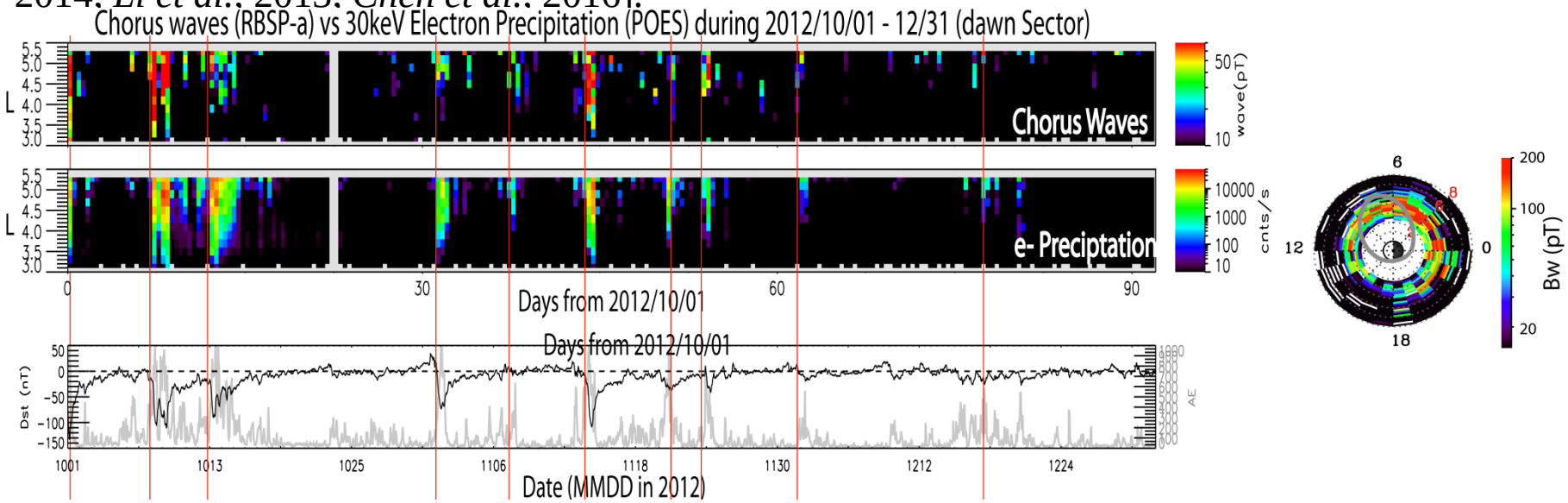
2. Background: The Status Quo

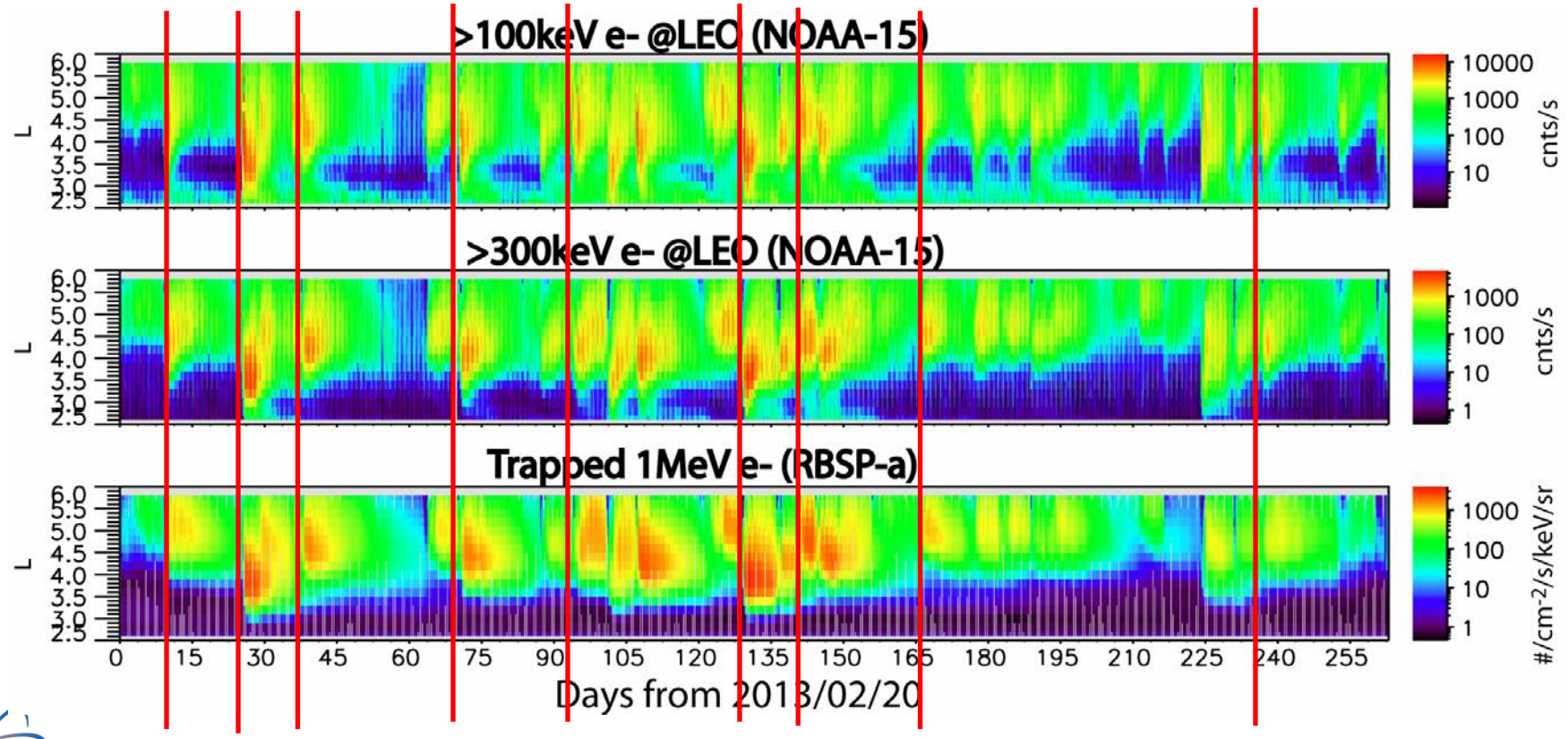
- ❑ Significant progress for radiation belt models [e.g., *Thorne et al.*, 2013; *Tu et al.*, 2014].
- ❑ Reliable model input parameters are the challenge.
- ❑ Some innovative methods have recently been developed for chorus waves [e.g., *Chen et al.*, 2014; *Li et al.*, 2013; *Chen et al.*, 2016].



- ❑ **Chorus waves alone do not necessarily lead to MeV electron energization.**
- ❑ **Even in-situ measurements will be gone in post-VAP era.**
- ❑ **There are existing predictive models for MeV electrons at GEO such as the REFM [*Baker et al.*, 1990] and *Lyatskey and Khazanov* [2008].**
- ❑ **MeV e- Global coherence has been studied[*Kanekal et al.*, 2001].**

3. Cross-energy cross-pitch-angle coherence for RB electrons

❑ **Significant one-to-one relation between the trapped relativistic electrons (1 MeV in our case)** observed by Van Allen Probes **and precipitating ~100s keV electrons** by NOAA POES at LEO.



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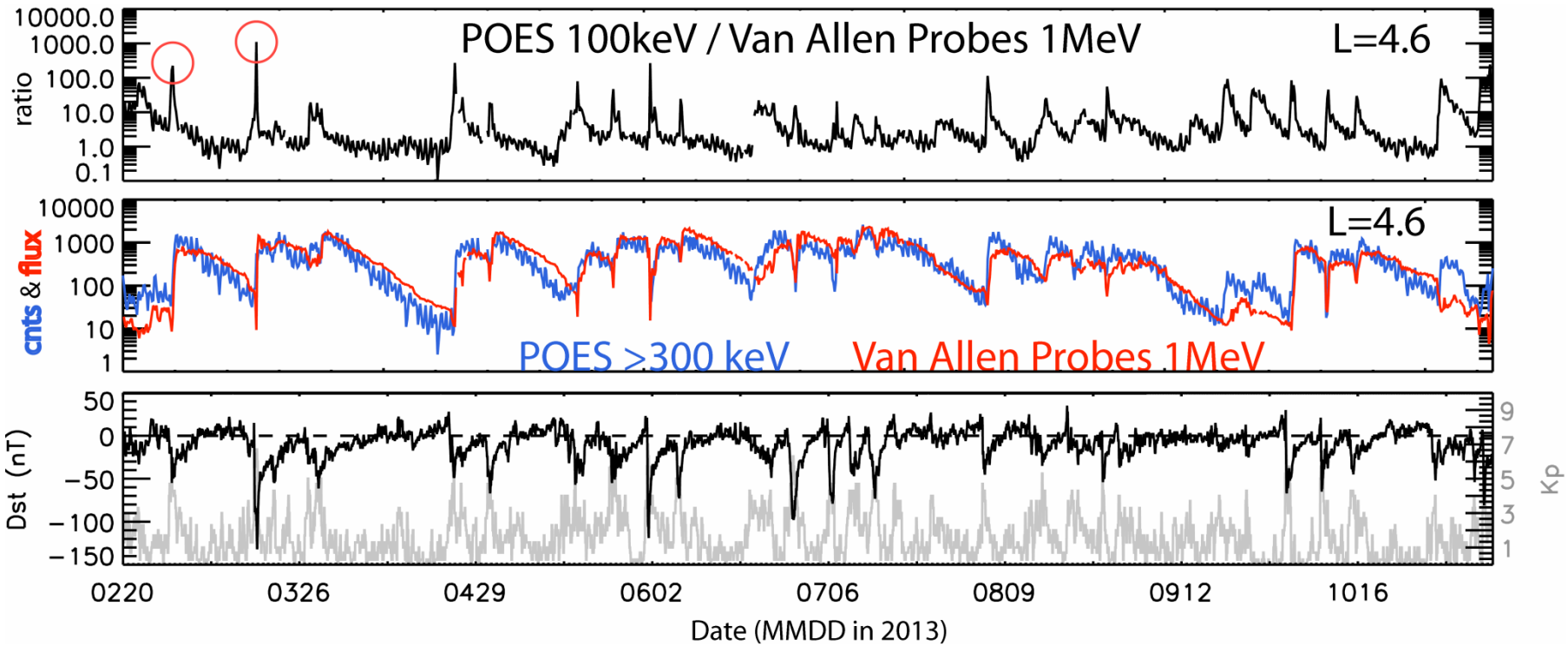
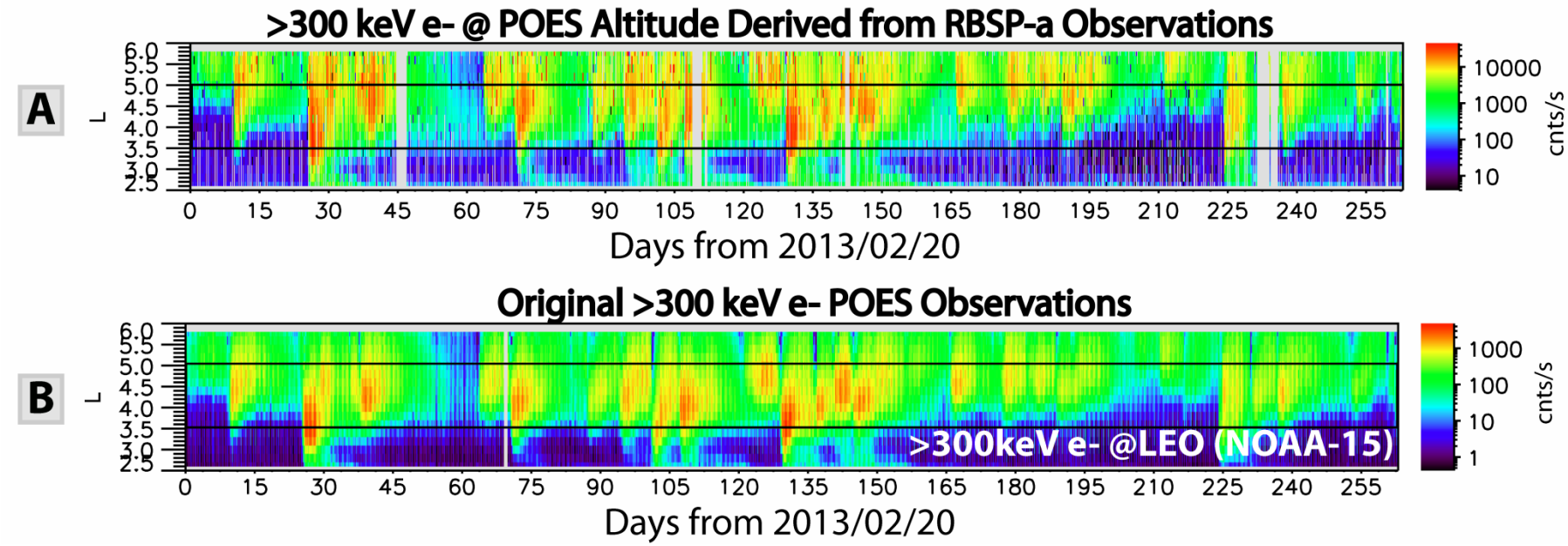
3. Cross-energy cross-pitch-angle coherence in RB electrons (cont'd)



❑ At L=4.6, the evolvement of >300keV precipitating electrons trace the MeV electron levels very well in each enhancement and decay afterwards, while the enhancements of >100keV precipitating electrons always lead MeV electrons by hrs.

❑ **>100keV electrons at LEO ➔ the precursor of enhancement of trapped MeV electrons; and the evolving >300keV elections at LEO➔ reliable proxy for MeV e-.**

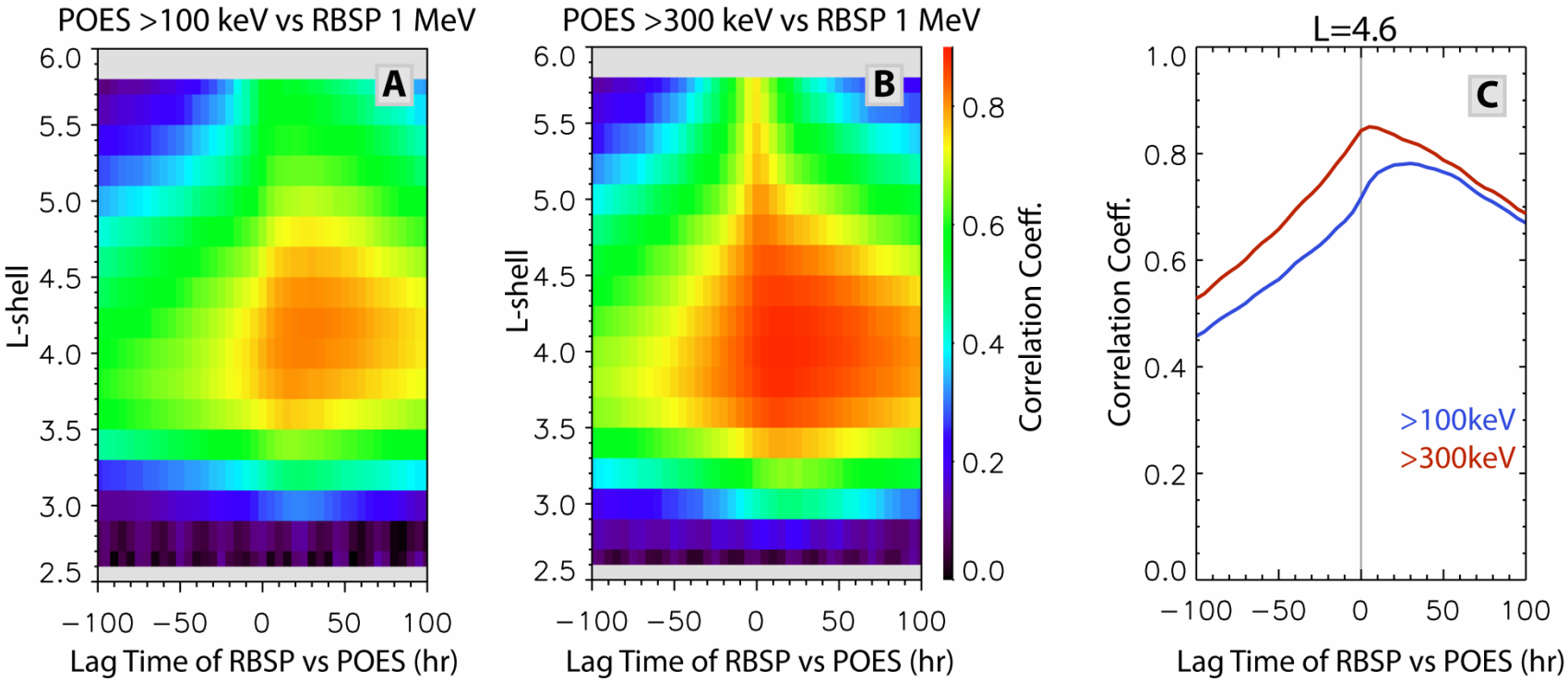
3. Cross-energy cross-pitch-angle coherence in RB electrons (cont'd)



❑ To confirm the newly discovered coherence is genuine but not due to the contamination of MeV electrons on POES MEPED ~100s keV detectors, we further examine the pitch-angle resolved MAGEIS data from Van Allen Probes.

❑ Dynamics shown in the pseudo data (Panel A) highly agree with those in original POES E3 data (Panel B) particularly at L-shells between ~3.5 – 5.0, therefore we believe MeV electrons have no significant effects on POES MEPED electron channels, and thus the cross-energy cross-pitch-angle coherence must be real.

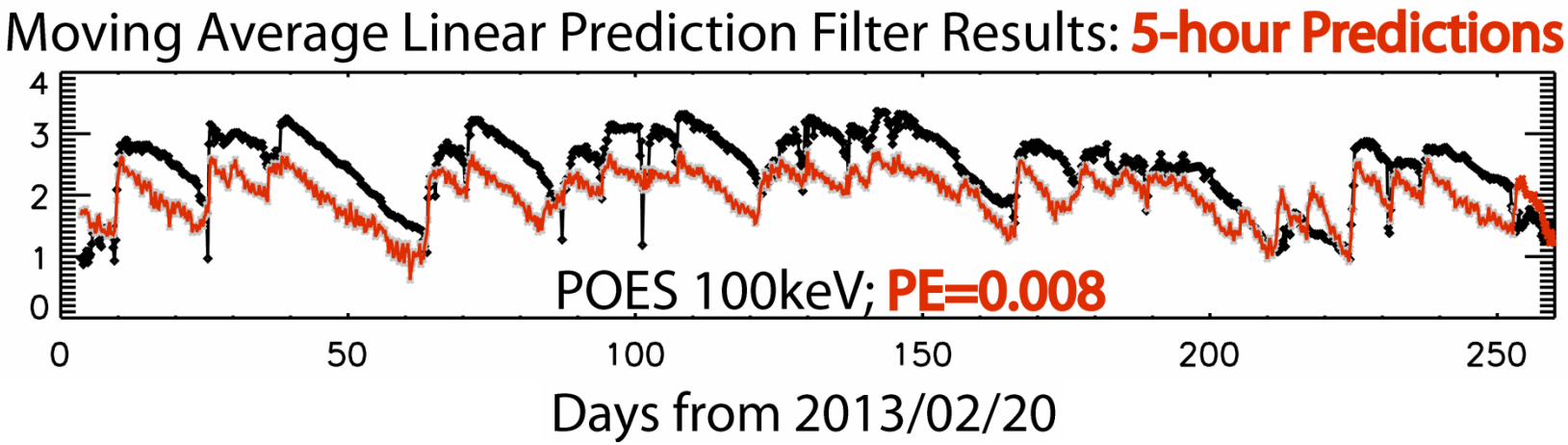
3. Cross-energy cross-pitch-angle coherence in RB electrons (cont'd)



❑ **High correlation coefficient values were found between the 5-hourly binned POES and RBSP data, particularly for L-shells in between ~ 3.5 – 5.0.** Specifically for L=4.6, the coefficient has a maximum value of **0.78 (0.85)** between >100 (>300) keV precipitating and MeV trapped electrons with leading time for >100 (>300) keV electrons is **~20 (~5) hours** ahead of 1 MeV electrons.

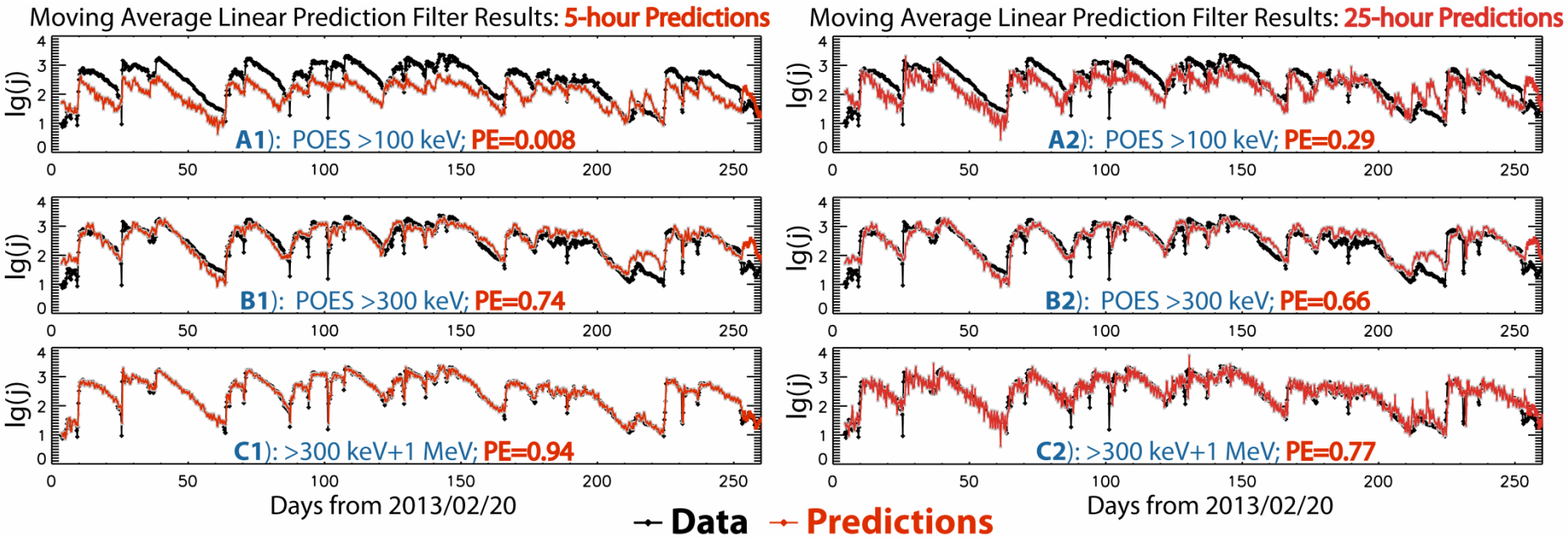
4. Linear prediction models for 1MeV electron at L=4.6

- The high coherence motives us to develop predictive filters for MeV electron.
- The filters use 5-hourly binned NOAA-15 data as input, either solely >100keV electron rate counts, or solely >300keV, or a combination of both.
- The 1MeV electron fluxes are predicted by linear filters ***J=Aj***
  - ***A*** the filter vector is solved by the SVD algorithm,
  - ***J*** is the MeV electron predicted for *n* time steps ahead
  - ***j*** are the low-energy electrons at times *t, t-1, …, t-m-1* (m is the number of total time points used by the filter)
- Predictions can be made for various time steps ahead.



Observations Predictions

4. Linear prediction models for 1MeV electron at L=4.6 (cont'd)



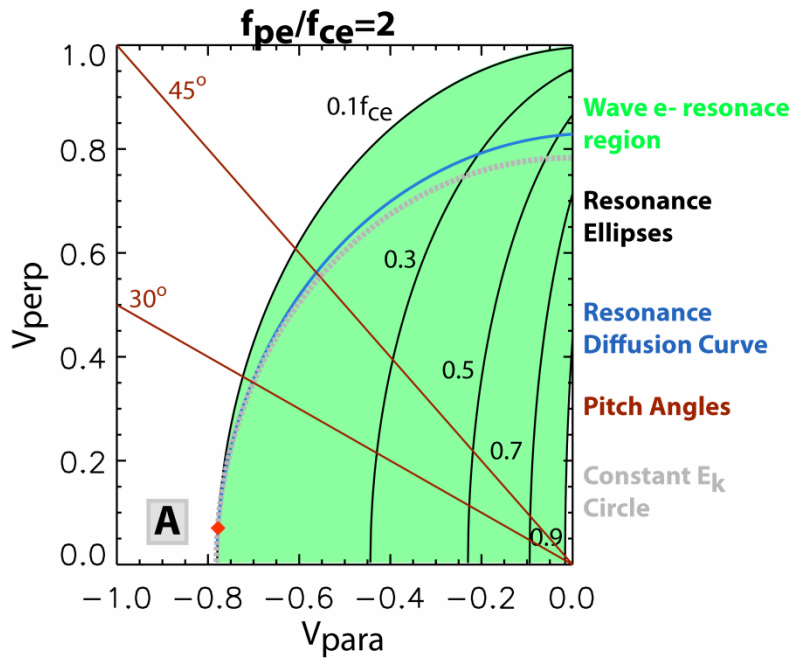
- **For 1-time-step (5 hr) predictions,** the model using >100keV has the lowest performance efficiency (PE) value; however, this model still catches the commence of each MeV electron enhancement event. **Models using either >300keV and combined POES data have much higher PE values of 0.74 and 0.72** (comparable to the 0.71 for REFM at GEO for 1-time-step–ahead (1 day) prediction).
- **For 5-time-step-ahead (25 hr) predictions**, the model using >100keV electrons improves, mainly due to improved fittings after MeV electron enhancement. **Models using >300keV electrons still has the highest PE of 0.66,** which is very different from REFM whose PE degrades very quickly with increasing forecasting time.

5. Explanation for the coherence

❑This cross-energy coherence suggests that **trapped electrons with originally 1MeV energy precipitate with energies broadly distributed over <1 MeV**. This should be considered when one examines the loss rate of trapped electrons through precipitation.

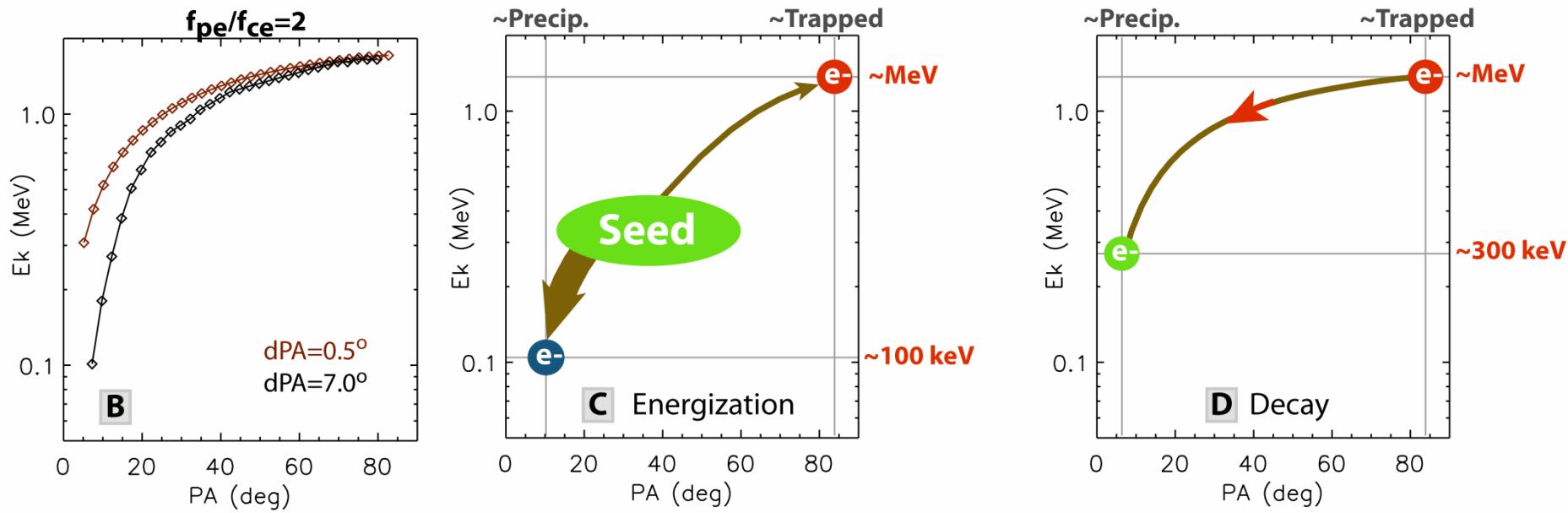
❑ This physics picture is quite natural when we consider how waves resonate with particles and change their velocities. e.g., **in the cyclotron resonance with chorus waves, electrons gain energy with increasing pitch angles, and loss energy with decreasing pitch angles**.

❑ Here we use the Lagrangian description to illustrate this WPI.



❑ **Here shows the velocity space in which test electrons have normal resonance with right-handed whistler-mode chorus waves (within the 0.1-0.9 fce range).** The green-shaded region indicates the space WPI occurs and each black curve is the resonance ellipse calculated for one wave frequency with a given plasma parameter. The red point indicates the starting location of a test electron, which is resonating with 0.1fce wave and moves along the diffusion curve (blue) by conserving its kinetic energy in the wave reference. Outside the WPI region, an electron may be static in a 1D case or move along a circle (gray) with constant energy in the lab reference and change its local pitch angles (red) in a 2D case.

5. Explanation for the coherence (cont'd)



- ❑ Case 1 with moderate WPI (red curve in left panel) has a small equatorial pitch angle change after each bounce movement, equivalent to Daa~10^2rad^2/day; case 2 has strong WPI (black) with a large change, equivalent to Daa~10^4rad^2/day .
- ❑ During a energization event (central), after the seed electrons are injected, due to the very strong WPI, majority of those electrons are diffused toward the loss cone while a small portion is accelerated up to above MeV levels.
- ❑ During the slow decay(right), due to the weaker but relatively steady and efficient WPI, MeV electrons are diffused into the loss cone with decreasing energy at ~300 keV (like the red curve in left panel).

Summary and Conclusions

- We had a new discovery of the cross-energy cross-pitch-angle coherence for the outer radiation belt electrons.
- Based on the discovery, we developed high-fidelity predictive models for 1 MeV electron at L=4.6 with inputs only from POES ~100s keV observations, and the models can be easily extended to other L-shells.
- This coherence can be explained by the classical WPI theory, with two cases of numerical calculations are shown here.
- This preliminary study reveals new important features for radiation belt dynamics, adds new science significance to a long existing NOAA space infrastructure, and hints us a new direction for developing predictive tools for the space community. Further detailed studies should enable us to remote-sense and forecast MeV electrons from the LEO region in the future.

Related publications:
1. Chen et al. (2016), Forecasting and remote sensing outer-belt relativistic electrons from low-Earth-orbits, Geophy. Res. Lett., 43, 3, 1031-1038, 10.1002/2015GL067481
2. Chen et al. (2014), Global time-dependent chorus maps from low-Earth-orbit electron precipitation and Van Allen Probes data, Geophy. Res. Lett., 41, 10.1002/2013GL059181