Recent Advancements on the Sources of the Inner Radiation Belt Particles

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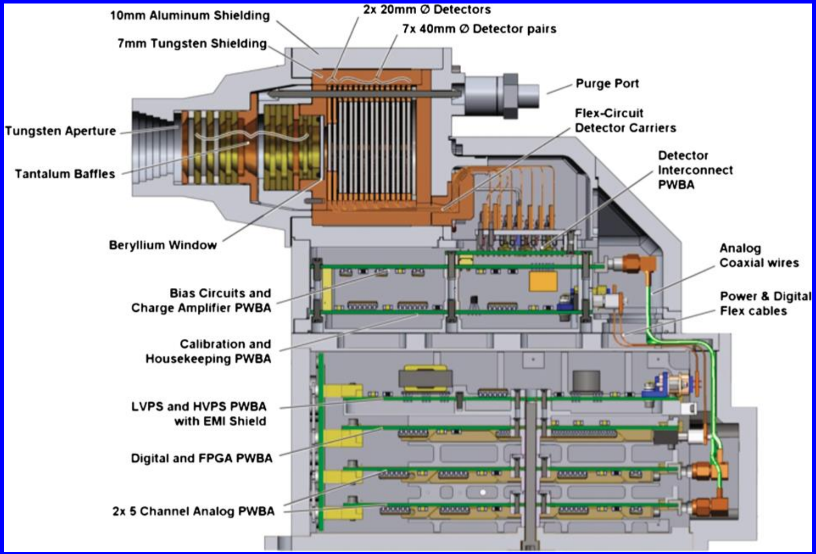
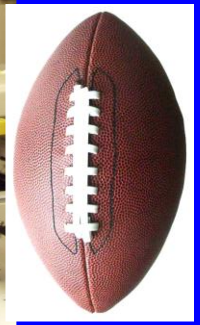
Van Allen Probes/REPT



3U CubeSat: Colorado Student Space Weather Experiment (CSSWE)/REPTile

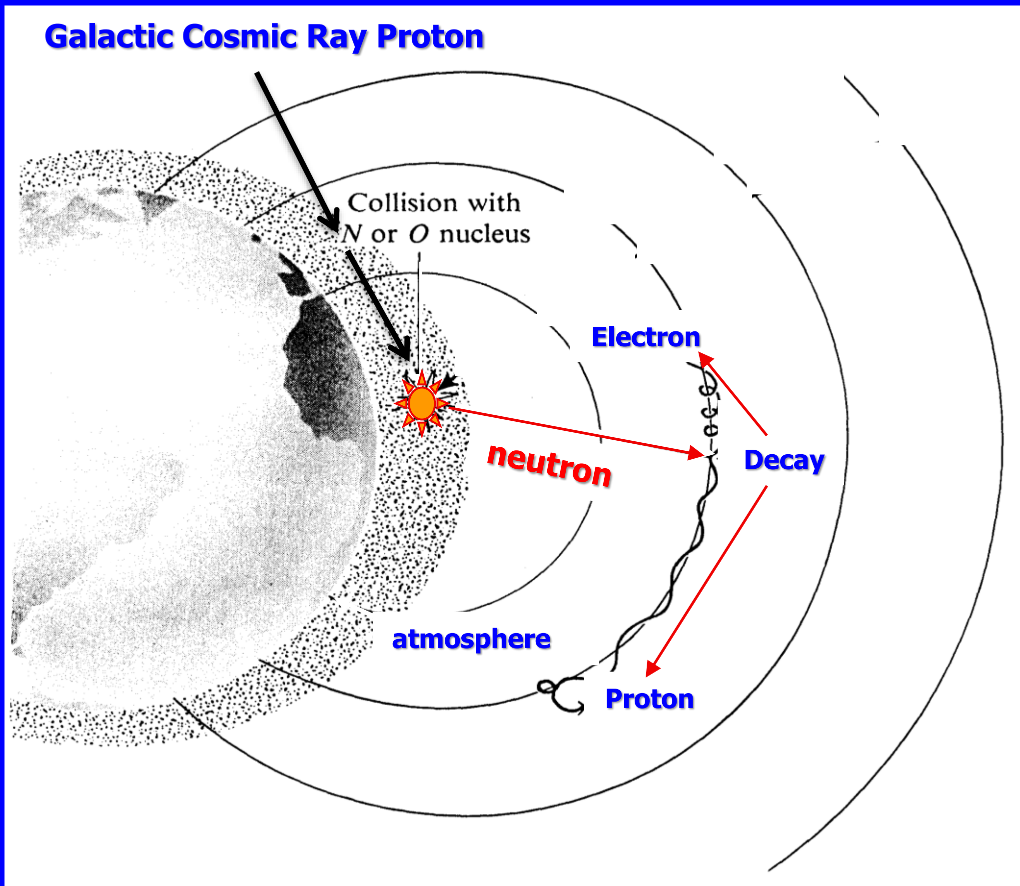
- Involved **over 65 students**
- Launched: **9/13/12 (>2 yr op)**
- Orbit: **~480 km x 790 km, inclination 65^0**



- Inner belt (L ≤ 2) consist of energetic protons and electrons
  - Protons: CRAND and Solar Energetic Particles
  - Electrons, >1MeV: Rarely seen, only during extreme SW conditions
  - Electrons, <1MeV: Commonly seen, from <u>CRAND</u> and Outer Belt

CRAND electrons ➔ neutron density

Inner-Zone (L ≤ 2) Proton Production Mechanisms

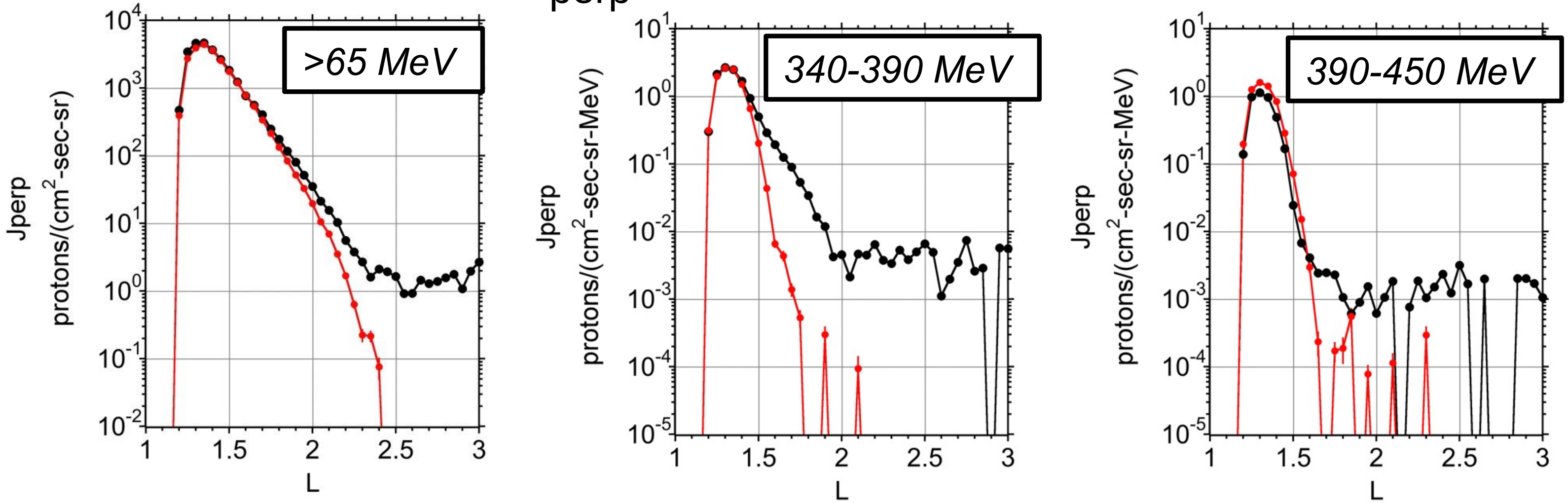


Fast neutrons made by direct interaction of high-energy cosmic rays: knock-on neutrons

proton + electron + neutrino (production of ≥10 MeV energetic protons (L ~ 1.5) that can be trapped). This mechanism is also referred to as CRAND: Cosmic Ray Albedo Neutron Decay

The trapped inner belt protons (>65 MeV) measured from Van Allen Probes/RPS and OV1-20 are dramatically similar across a 41 yr interval

OV1-20 and RPS J_{perp} Versus L



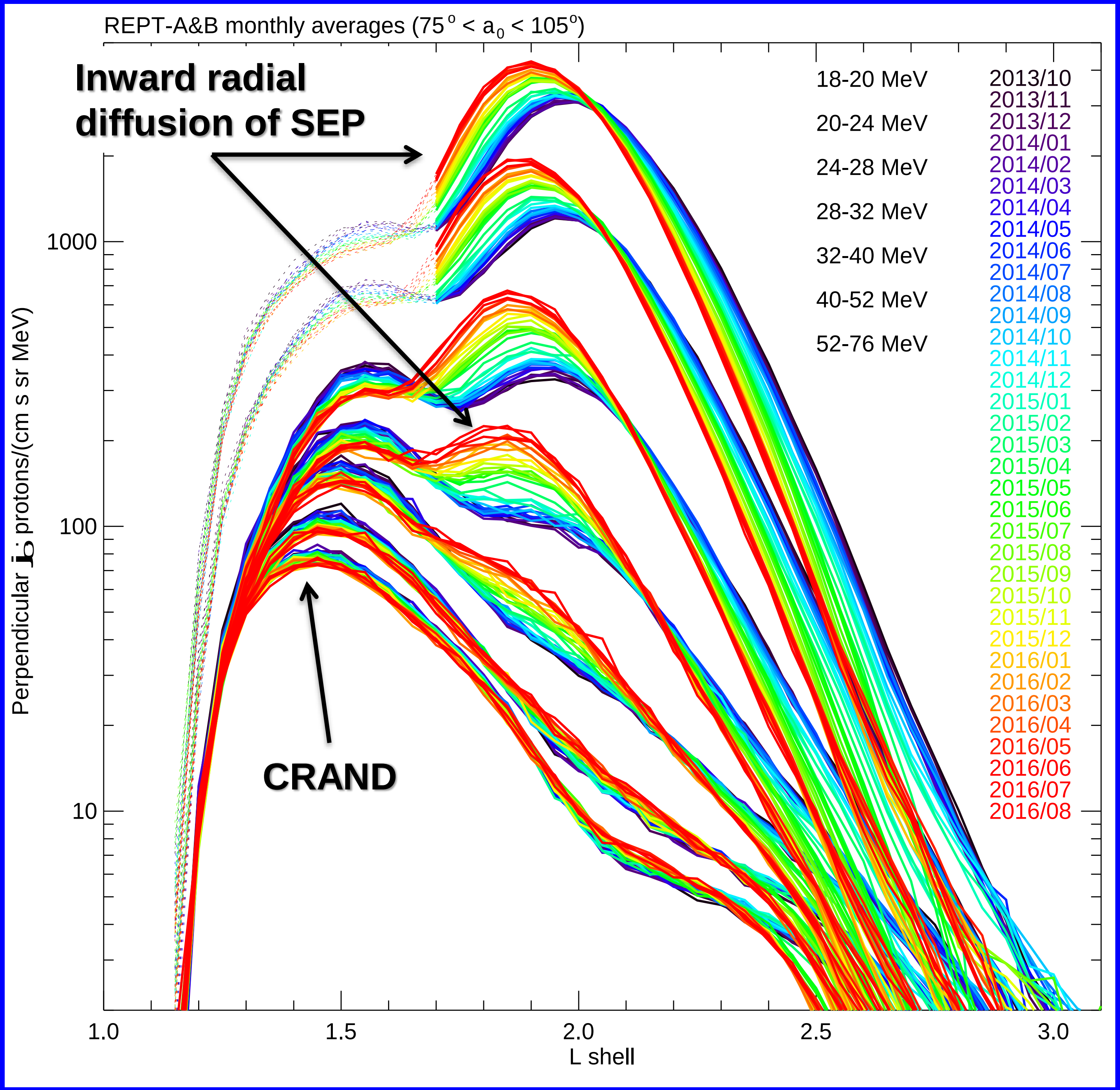
(Mazur et al., Fall AGU, 2014)

OV1-20 → **Measured in 1971**

RPS → **Measured in 2012**

The situation is very different for lower energy protons at the outer edge of the inner belt

Monthly averages of proton flux measured by REPT from 2013/10 – 2016/08 (extended from Selesnick et al., JGR, 2016)



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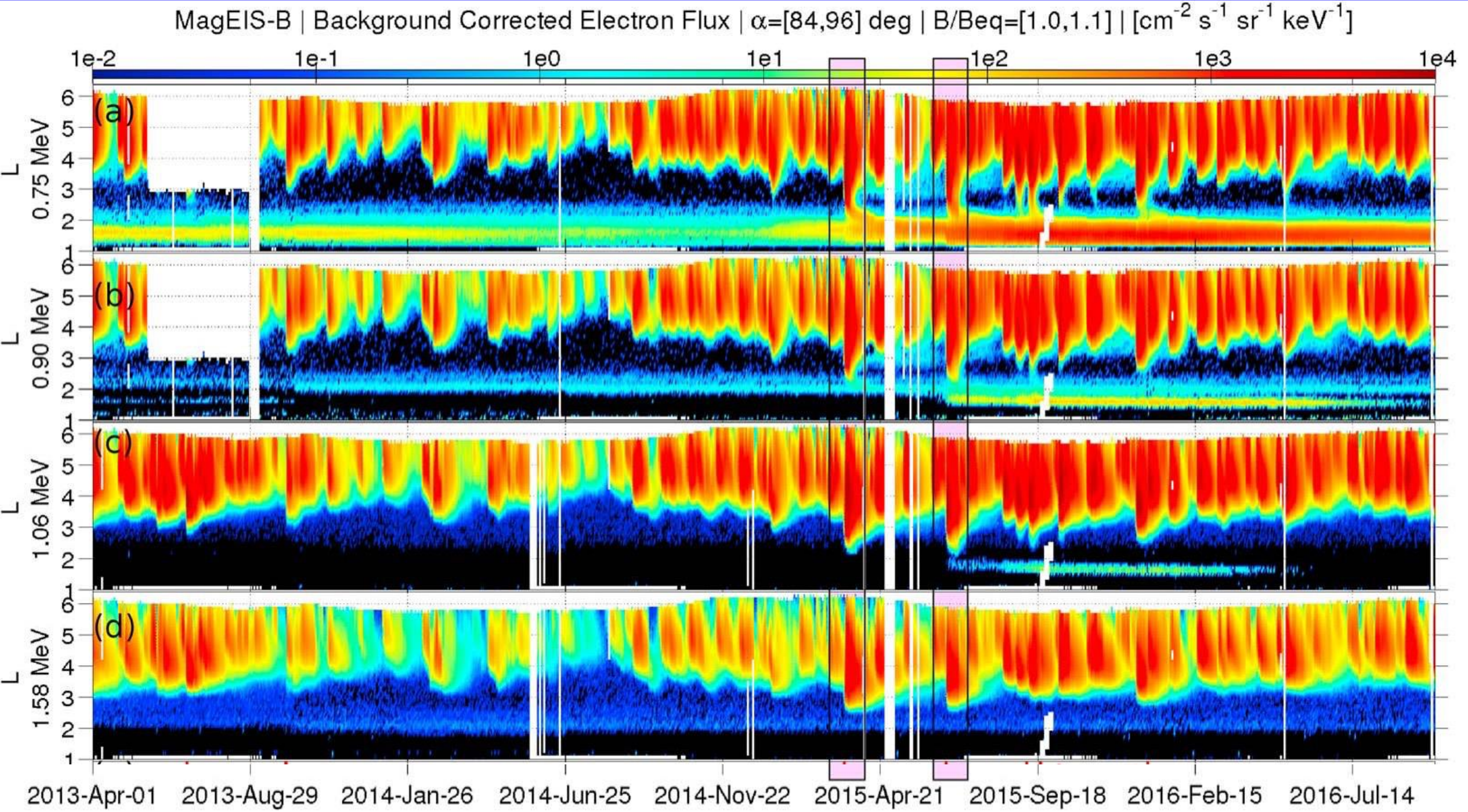
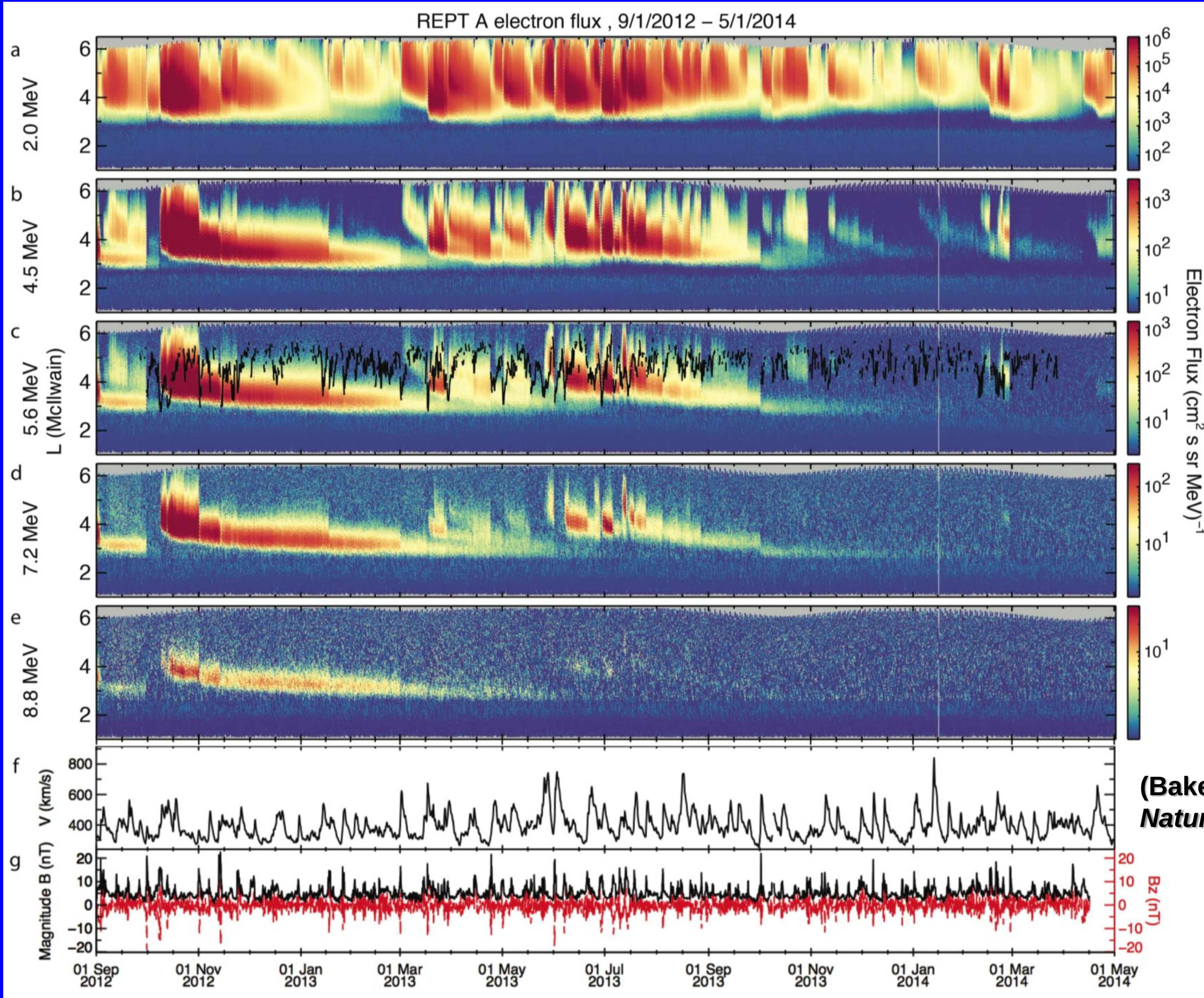
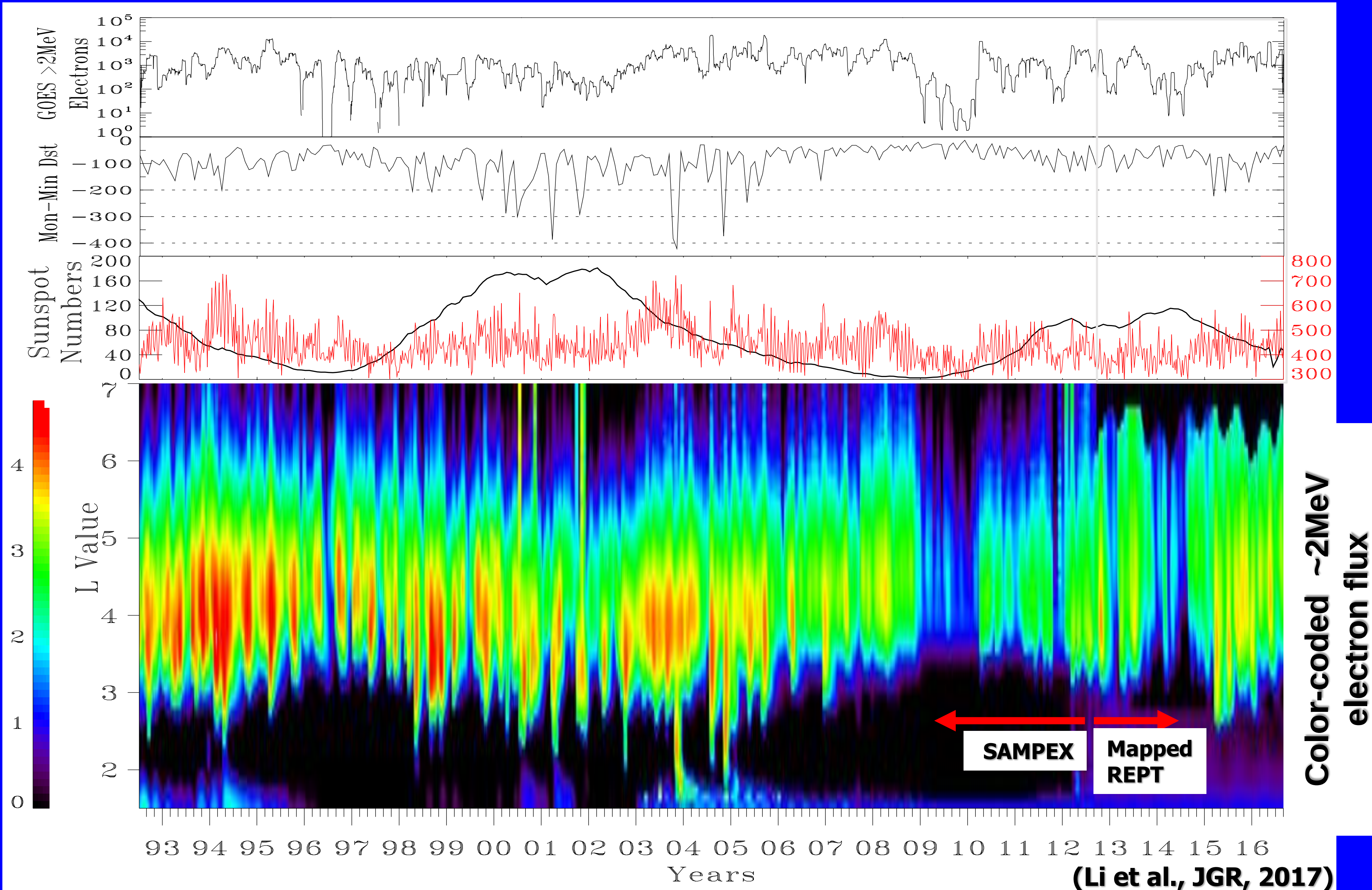
Li et al., JGR, 2015: Upper limit on the inner radiation belt MeV electron intensity
Fennell et al., GRL, 2015: … the inner radiation zone contains no MeV electrons …



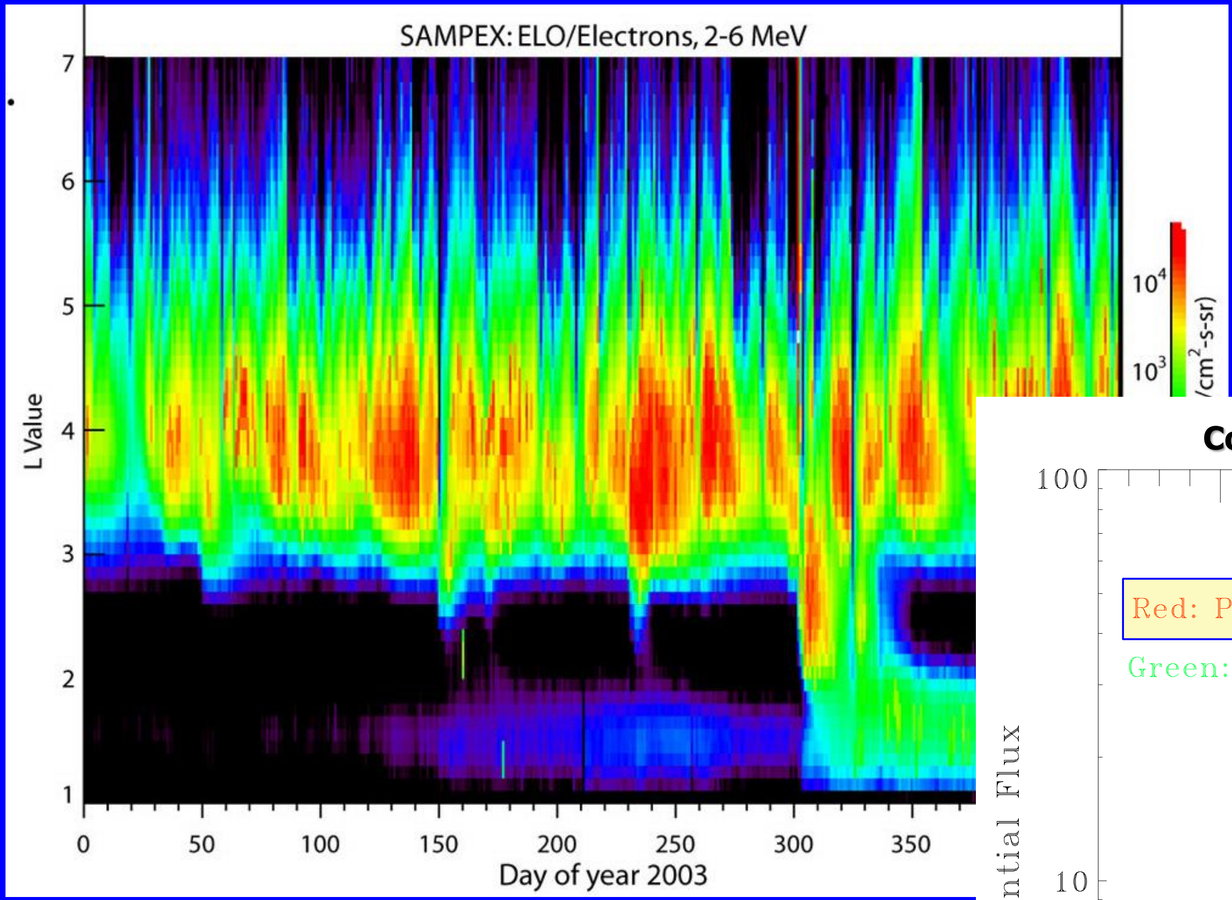
(Claudepierre et al., JGR, 2017)



(Baker et al., *Nature*, 2014)

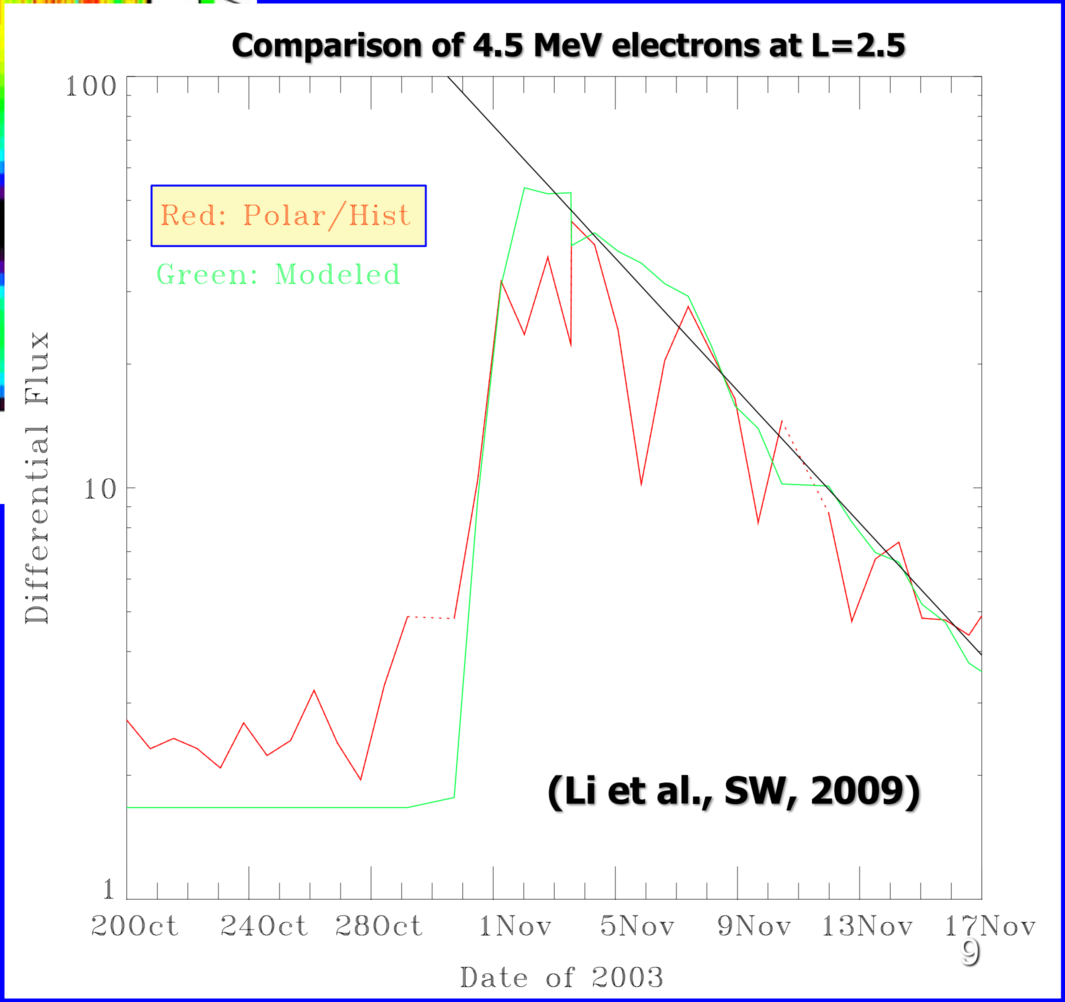


(Li et al., JGR, 2017)



(Baker et al., *Nature*, 2004)

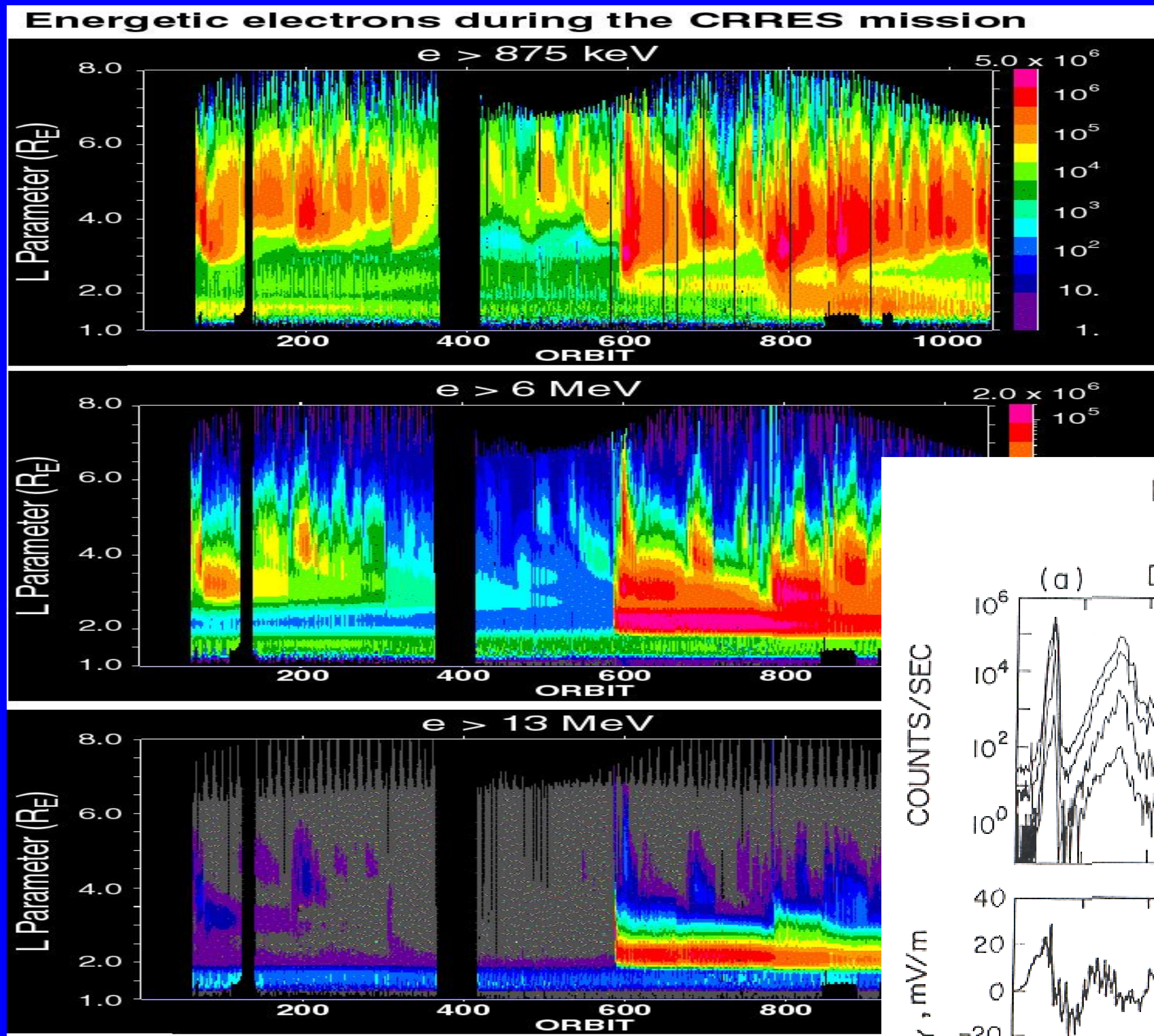
Injections of multi-MeV electrons into the slot region and inner belt did happen when the sun was much more active



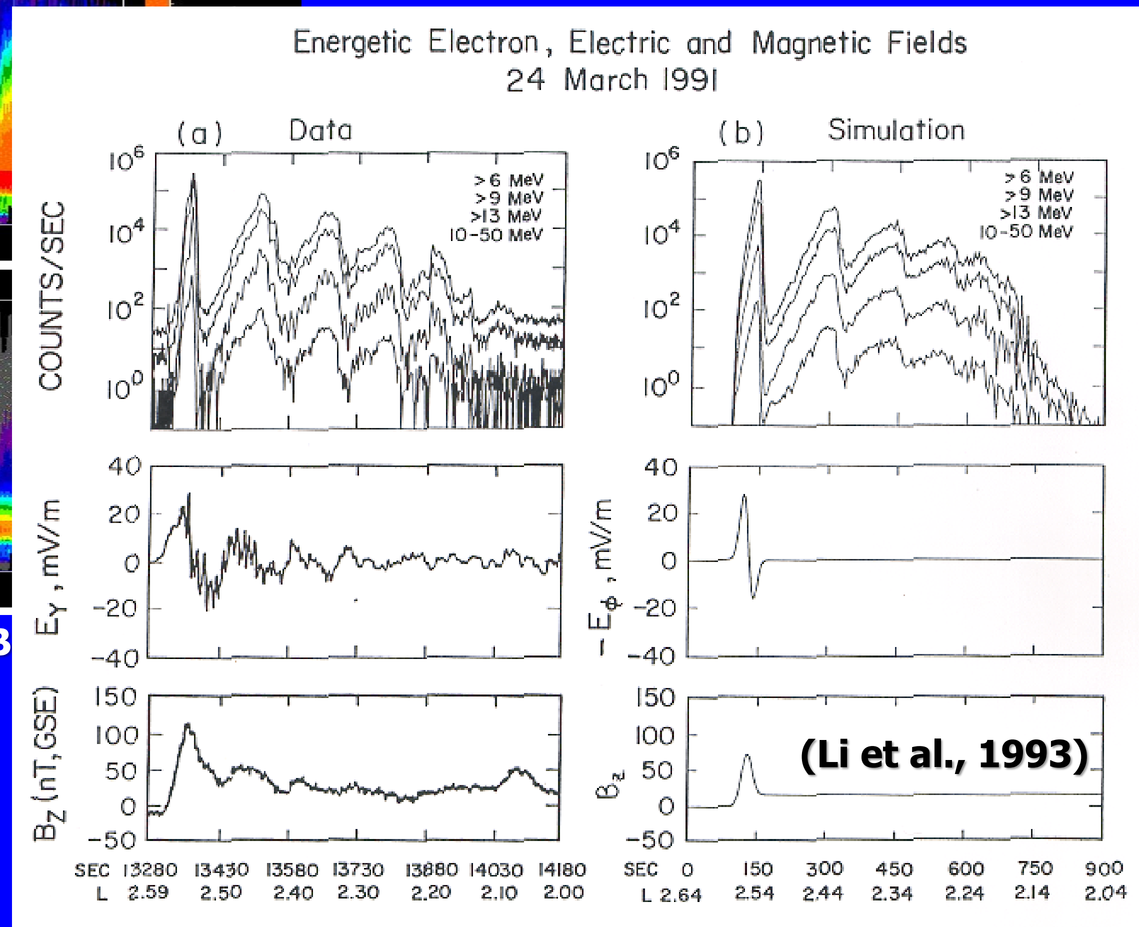
Horne et al., *Nature*, 2005: Wave acceleration of electrons …

Kim et al., *JGR*, 2016: Fast injection of the relativistic electrons (~1MeV) into the inner zone … the Bastille Day storm in July 2000

Injections of multi-MeV electrons into the slot region and inner belt <u>did happen</u> when the sun was much more active



(CRRES mission, 1990-1991, Courtesy of J. B



(Li et al., 1993)

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  - **Protons: CRAND and Solar Energetic Particles**
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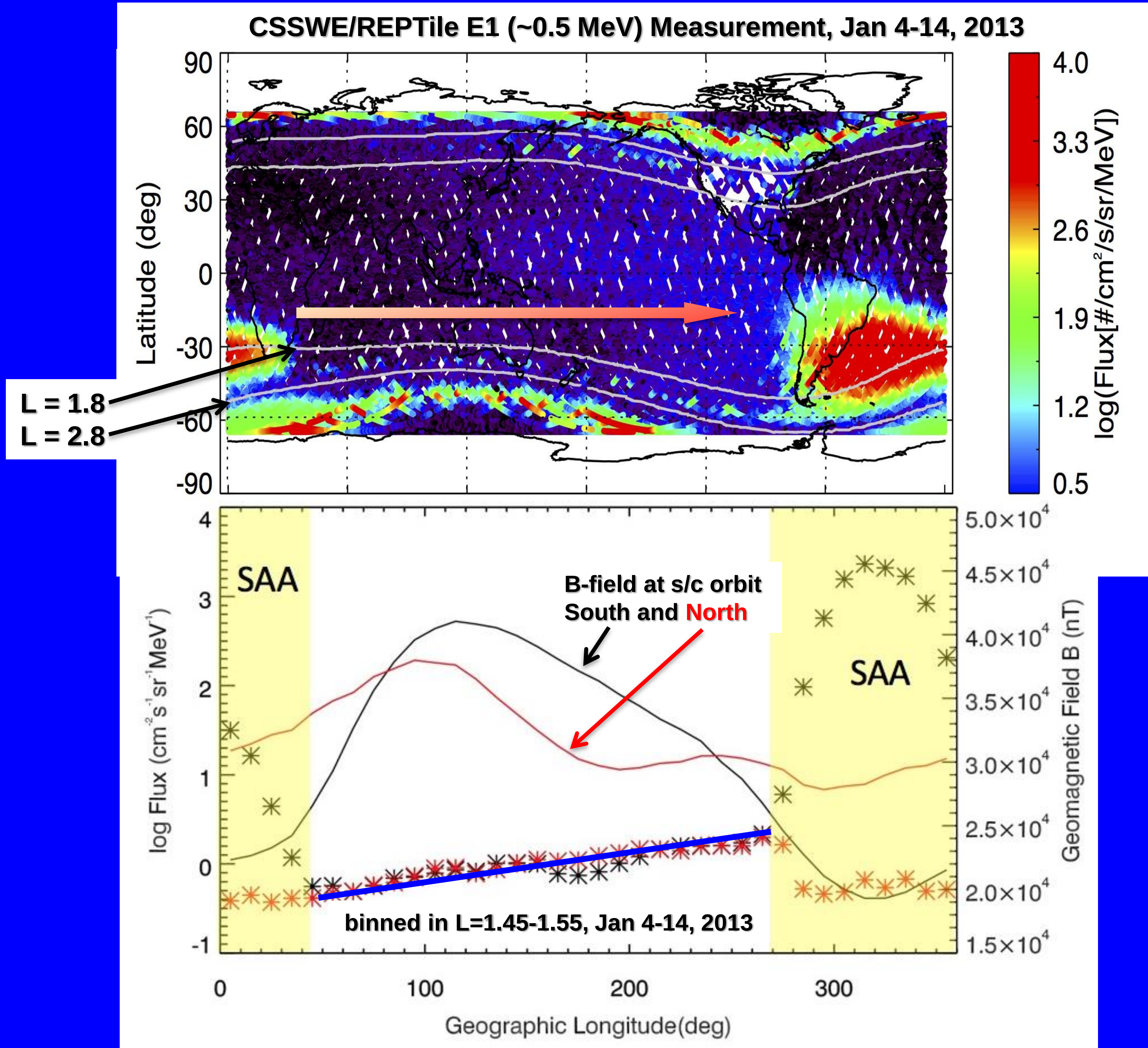
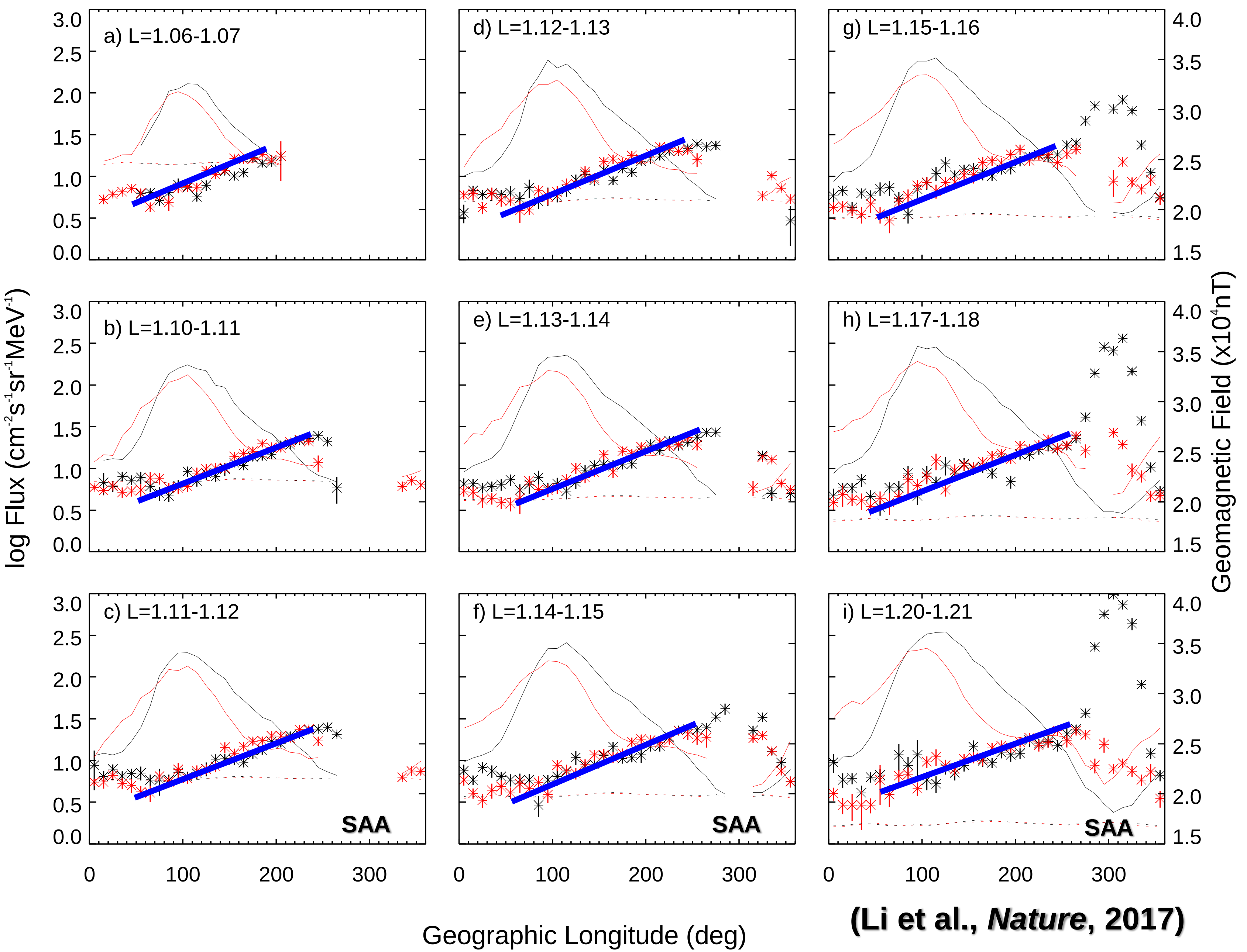
CRAND electrons → neutron density



CSSWE/REPTile E1 (~0.5 MeV) Measurement, Jan 4-14, 2013
Latitude (deg)
log(Flux[#/cm²/s/sr/MeV])
L = 1.8
L = 2.8
SAA
SAA
B-field at s/c orbit
South and North
binned in L=1.45-1.55, Jan 4-14, 2013
log Flux (cm⁻²s⁻¹sr⁻¹MeV⁻¹)
Geomagnetic Field B (nT)
Geographic Longitude(deg)

CSSWE/REPTile: 0.5 MeV Electrons for Jan 4-14, 2013



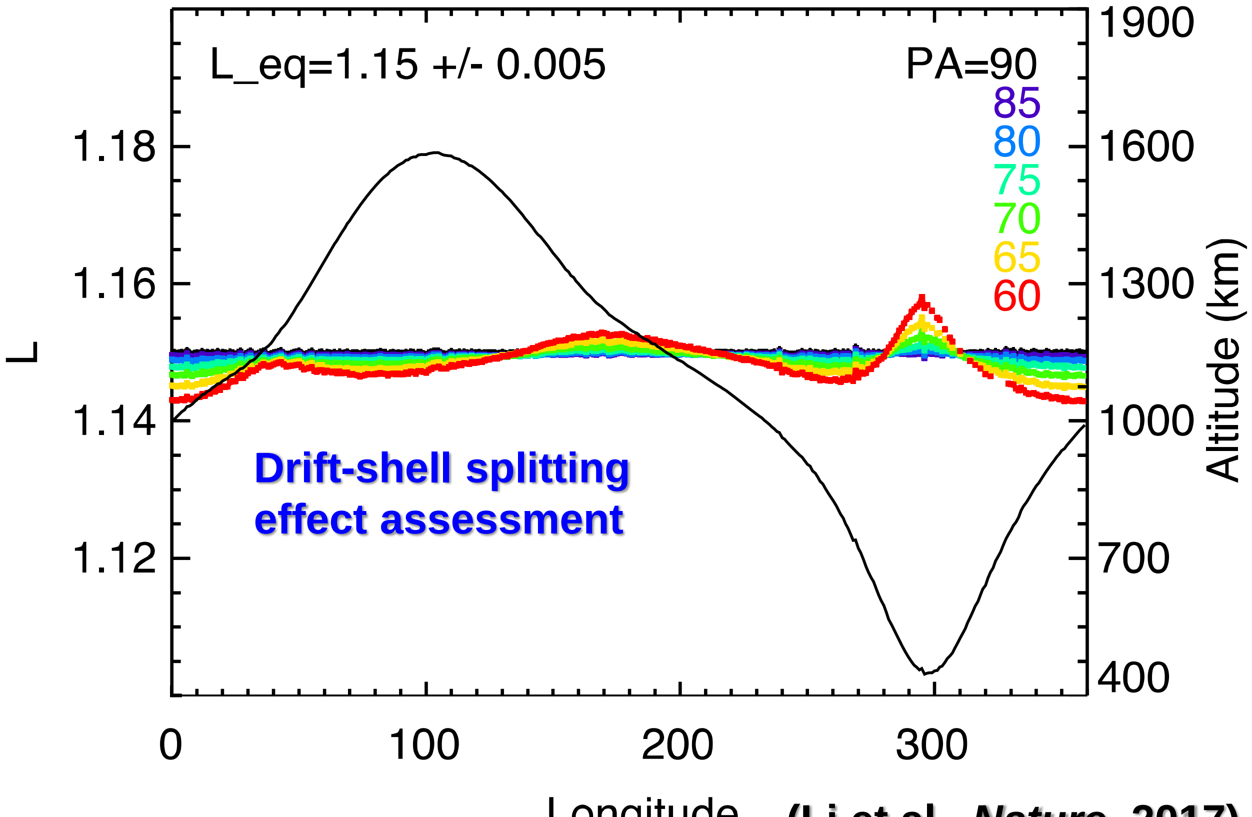
(Li et al., *Nature*, 2017)

Some possible explanations:

(1) Drift-shell splitting, stably trapped → quasi-trapped at lower L (△L~0.02)

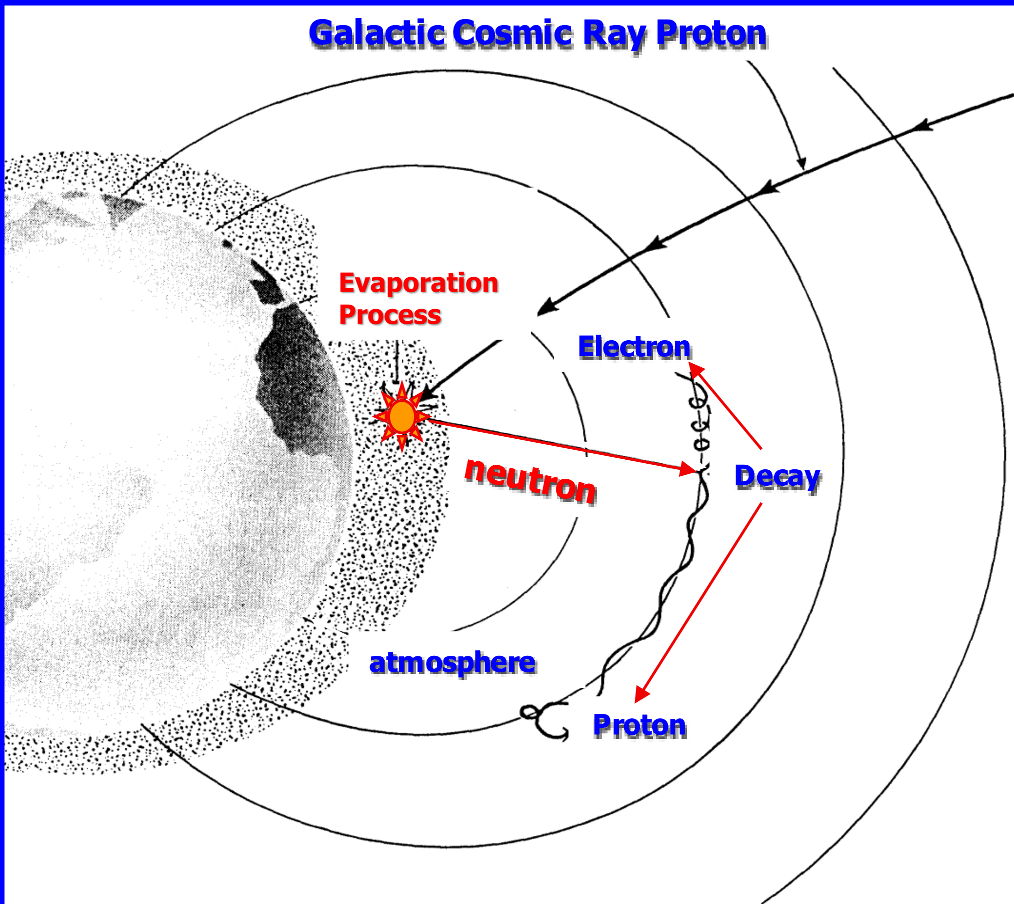
(2) L calculation uncertainties due to convection electric field (△L~ 0.01)

(3) Inward radial transport Not for the steady feature

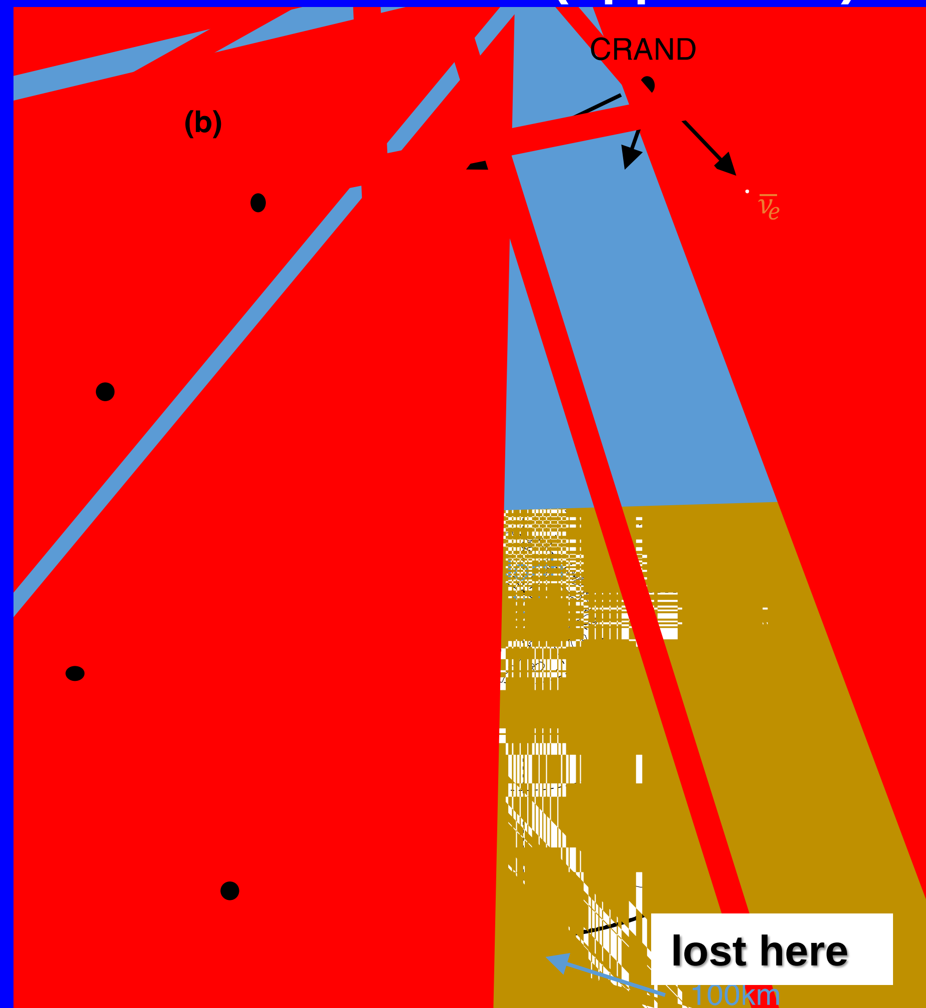


(Li et al., *Nature*, 2017)

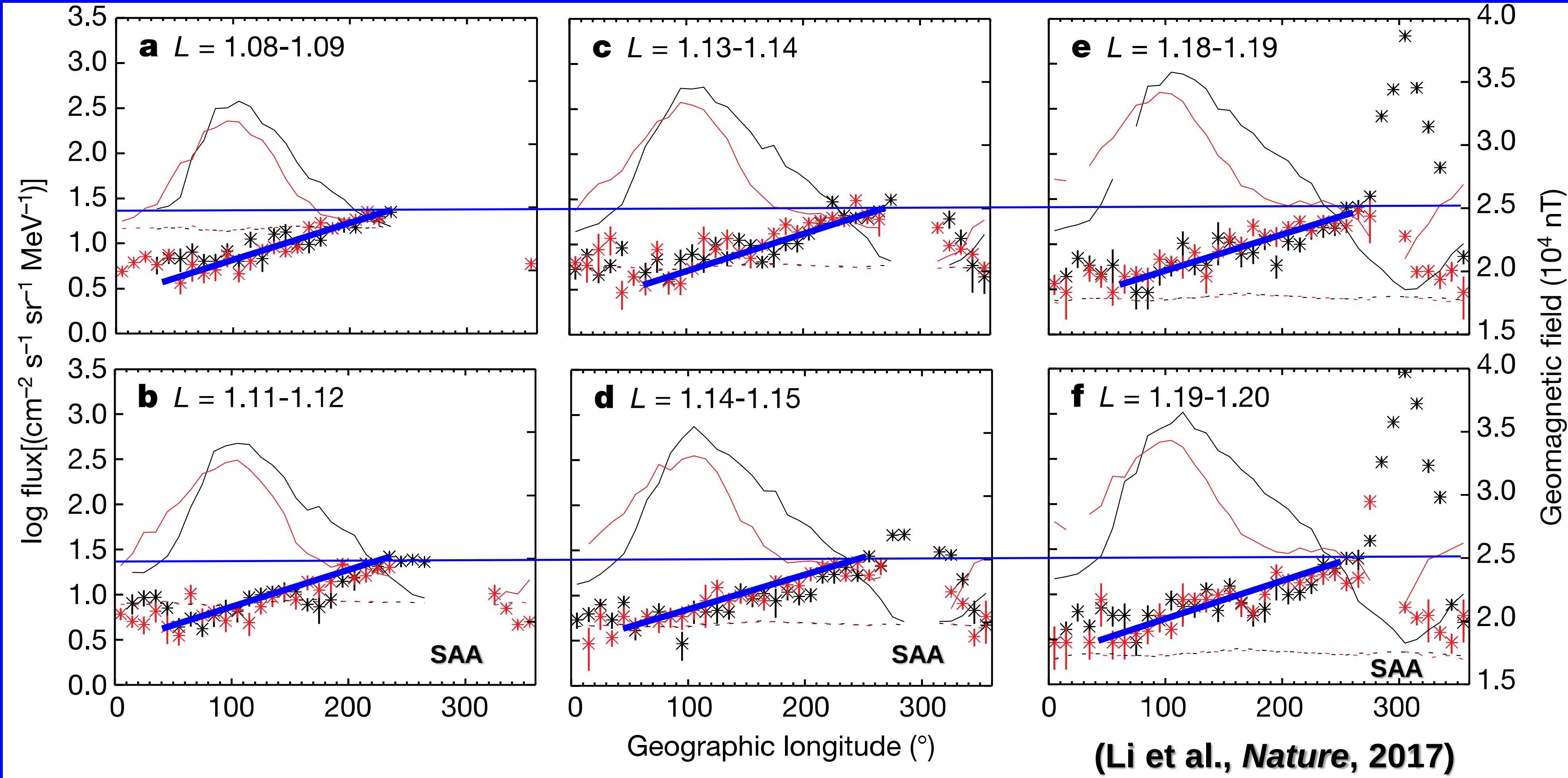
The only feasible explanation:
Cosmic Ray Albedo Neutron Decay (CRAND) via evaporation process



CRAND electrons are mostly from the β-decay of thermal neutrons:
$(m_n - m_p - m_e)c^2 \approx 782$ keV
(upper limit)



CSSWE/REPTile: 0.5 MeV Electrons for Oct 7-10, 2012



(Li et al., *Nature*, 2017)

First direct detection of CRAND electrons in near-Earth space

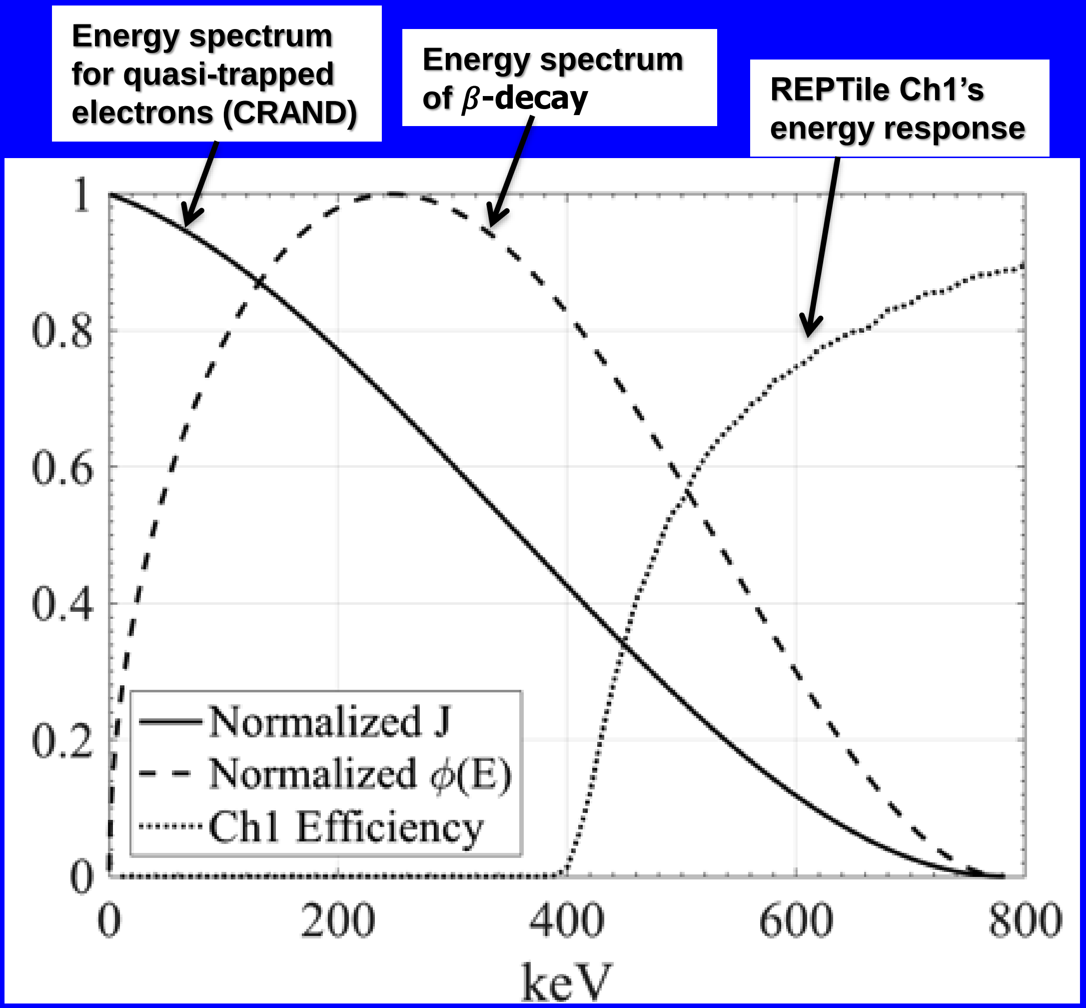
CRAND: the only source for the quasi-trapped electrons (L<1.14), then neutron density can be determined from the measured electron flux:

$$J(E) = \frac{nv}{4\pi}\frac{T_e}{T_n}\varphi(E)$$

For a 0.5 MeV electron at L=1.2, v: speed (2.6×10^{10} cm/s); T_e: drift period (1.5 hr); T_n: mean neutron lifetime (887 s), $\varphi(E)$: energy spectrum of β-decay

$$n = 4\pi\, J(E)\,\frac{T_n}{T_e}\,[\varphi(E)]^{-1}\, v^{-1}$$

<u>For the first time</u>, we determined:
$n = \sim 2\times10^{-9}\ cm^{-3}$ in near-Earth space.

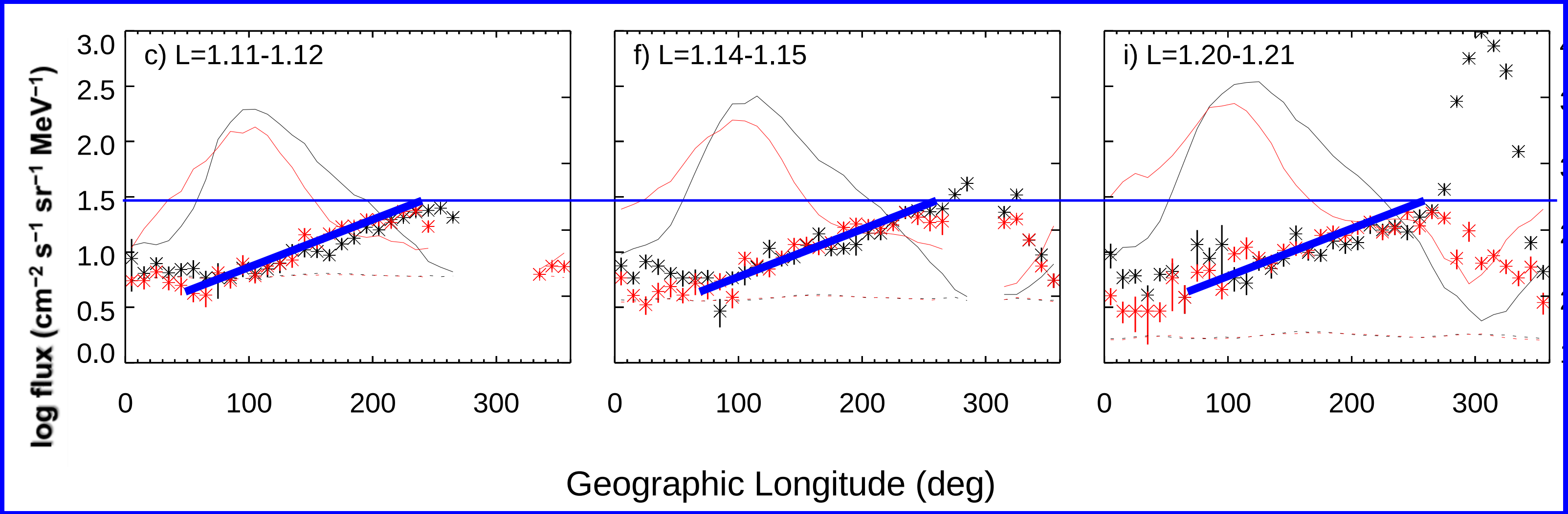


Attempts* were made to directly measure the thermal neutron density in space, but results were contaminated by locally generated neutrons from energetic particles striking on the spacecraft.

* Koga, K., Muraki, Y., Matsumoto, H. & Kawano, H. in *Selected Papers from the 30th International Symposium on Space Technology and Science* (under review)

CRAND: contributing to other regions as well, trapped and quasi-trapped

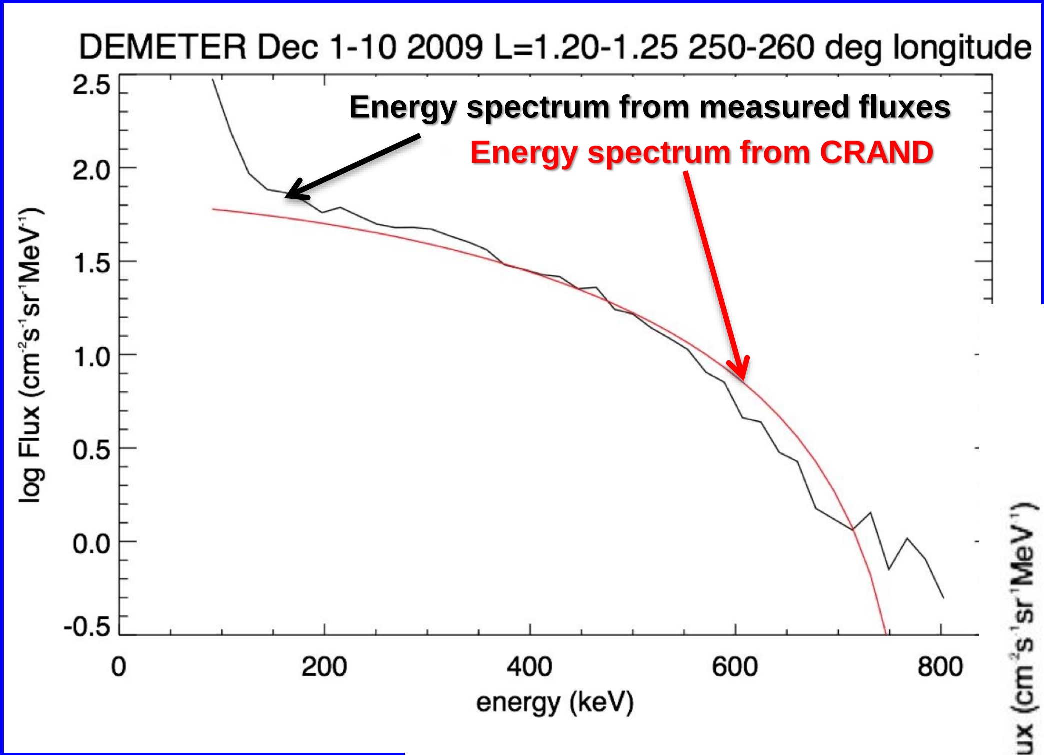
The quasi-trapped flux reaches about 25 at 0.5 MeV in less than ~1.5 hr. At this rate, in 30 days the intensity from CRAND would be about 10^3, comparable to the trapped level observed at *L* = 1.2 during quiet times.



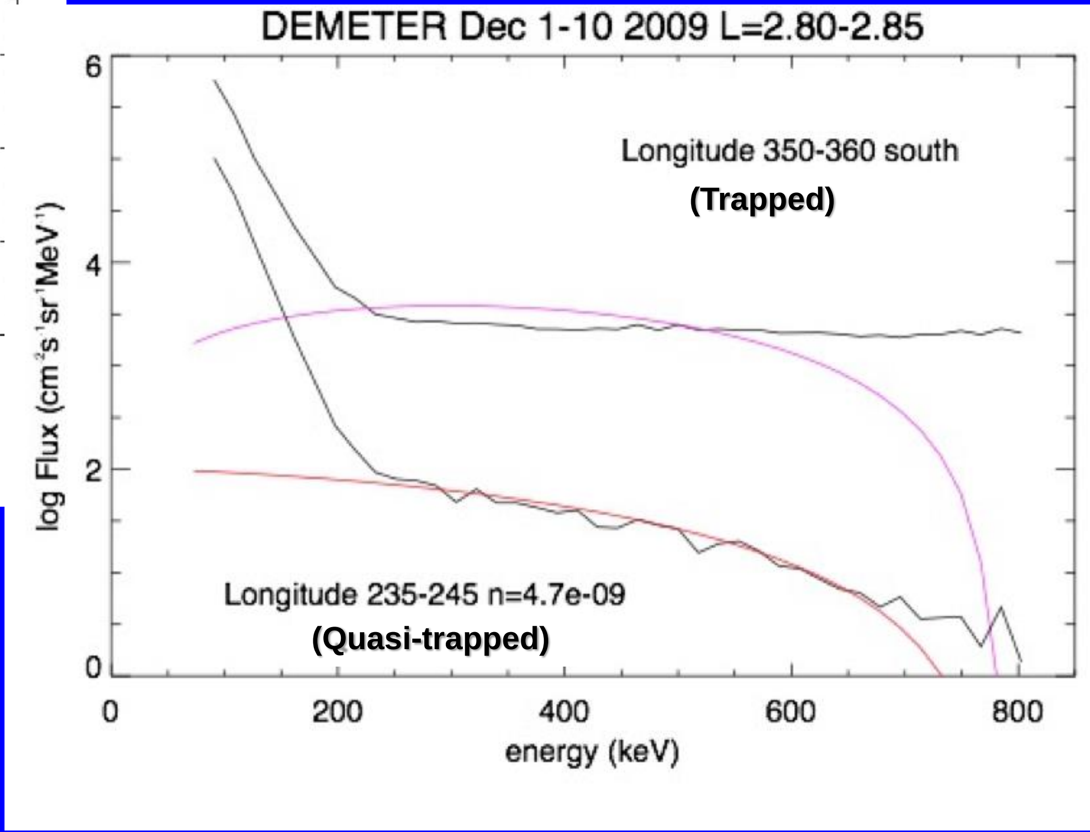
IMPLICATION: Source and Loss (pitch angle scattering) for the inner belt and slot region need to be re-visited.

Confirmation and extended study with other measurements

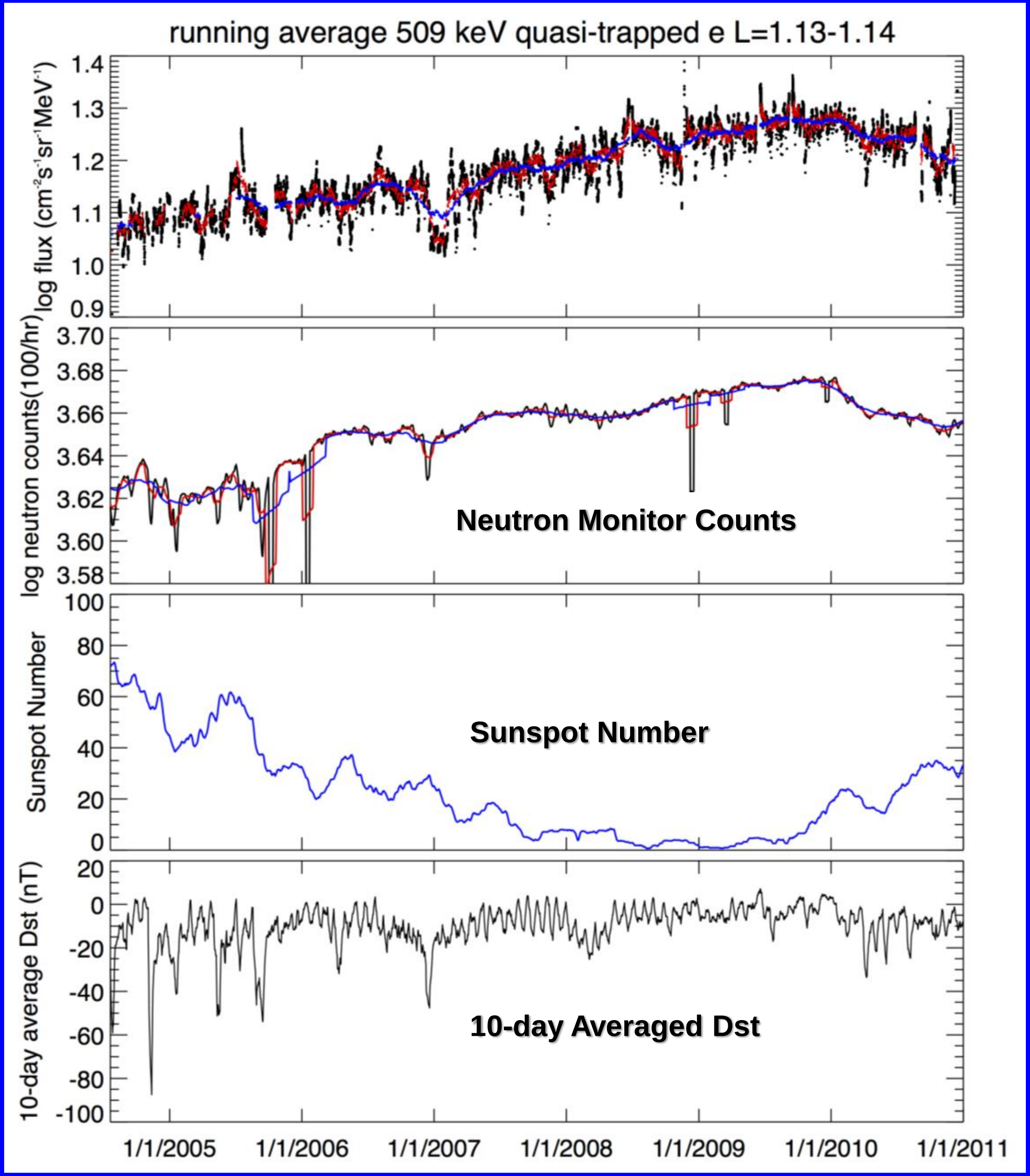
DEMETER: low polar orbit of 710 km altitude and an inclination of 98.3°



(Zhang et al., Fall AGU, 2017)



Solar Cycle Dependence of the Quasi-trapped Electrons



Conclusions

Inner belt protons, higher energy (>65 MeV) at lower L(<1.5), CRAND sources, are stable (RPS)

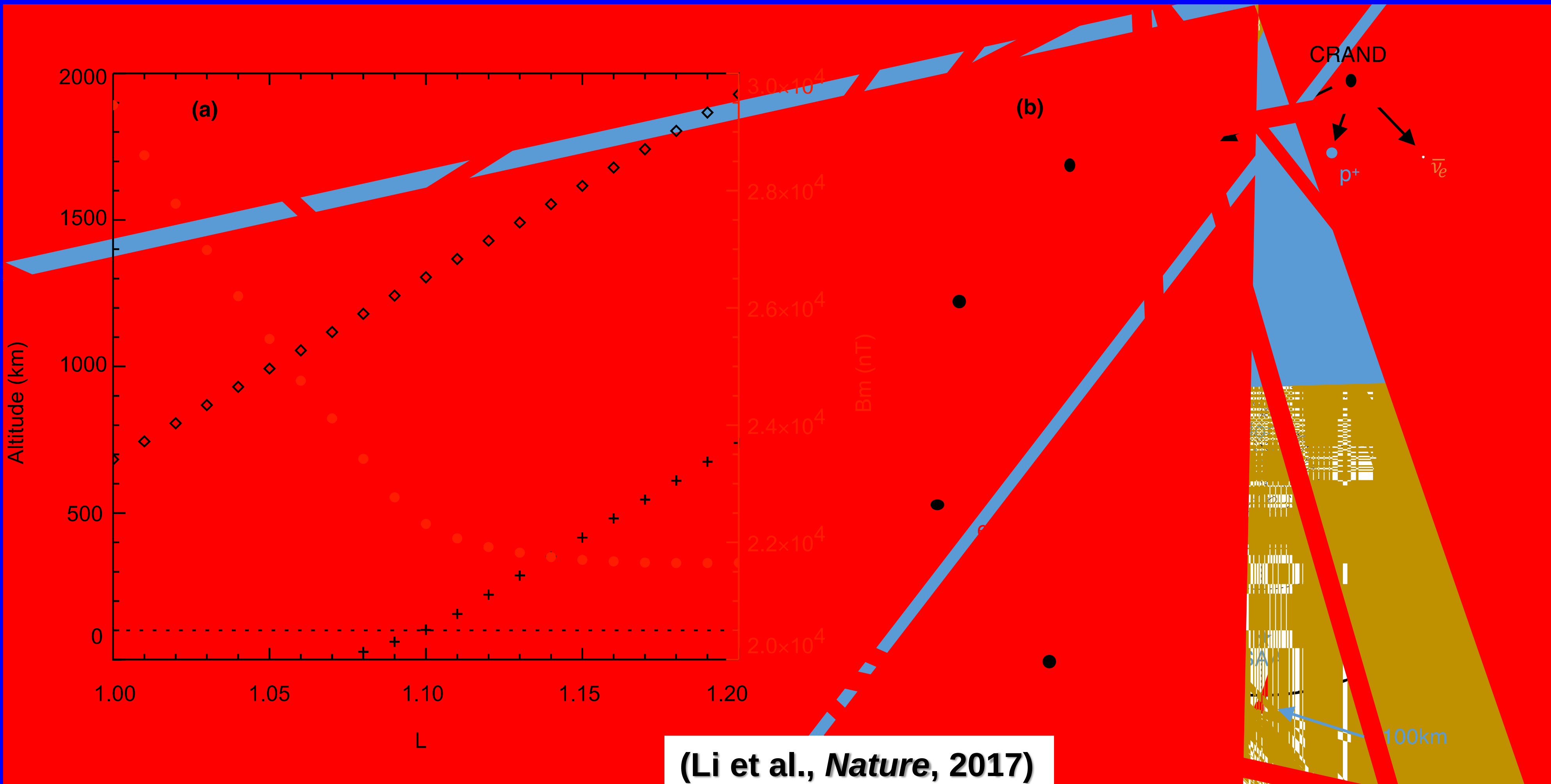
Inner belt protons, lower energy (<60 MeV) at higher L (>1.6), SEP sources, are much more dynamic than previously thought (REPT)

Enhancements of >1 MeV electrons in the inner belt occur only when there are strong solar wind disturbances (CRRES, SAMPEX, REPT, MagEIS, REPTile)

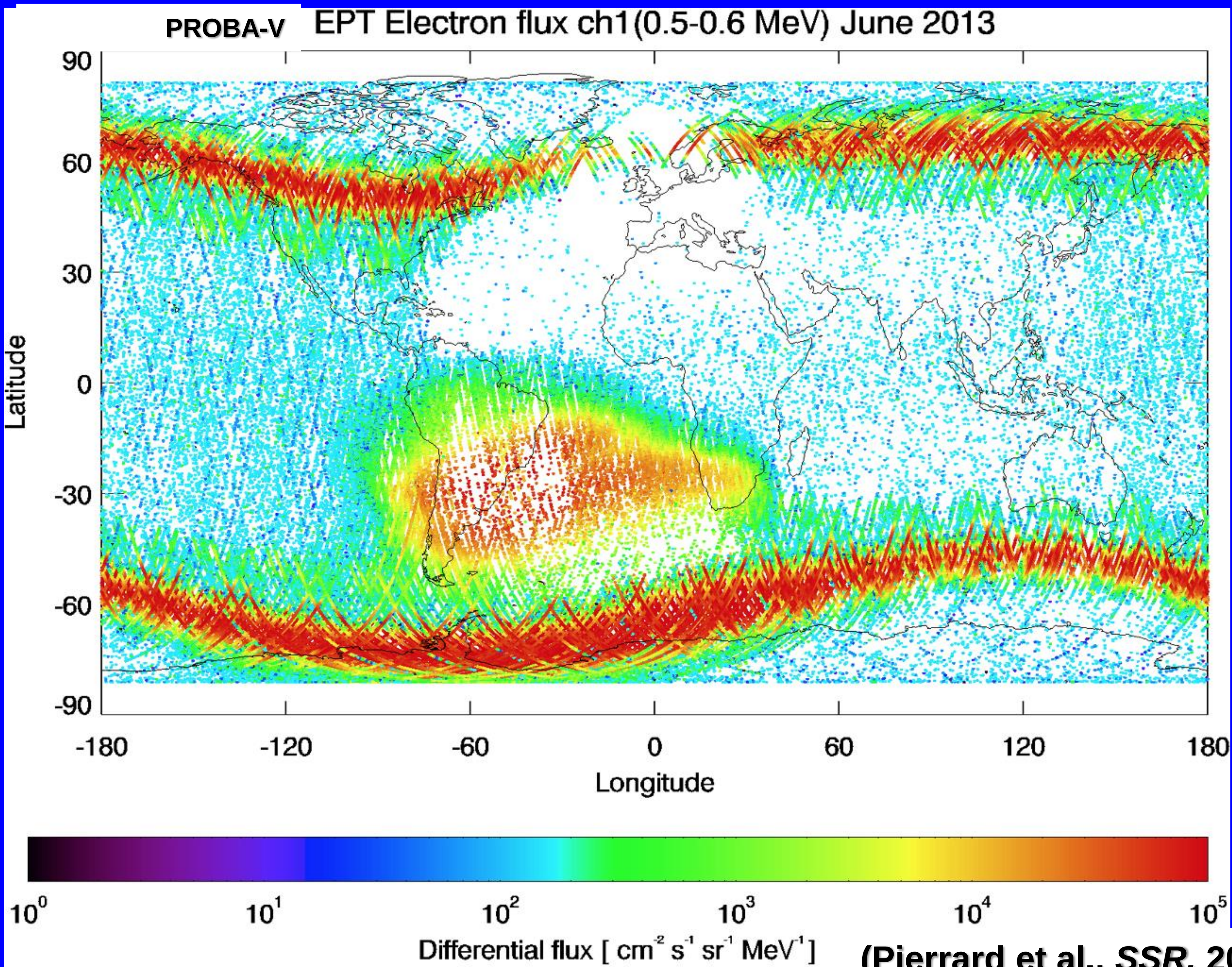
Based on CSSWE/REPTile measurements, <u>for the first time</u>:

(1) direct detection of CRAND electrons in the inner belt
(2) experimental determination of the neutron density in near-Earth space

IMPLICATION: Source and Loss (pitch angle scattering) for the inner belt and slot region need to be re-visited.



(Li et al., *Nature*, 2017)



(Pierrard et al., *SSR,* 2017)