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Supporting Information for

**Statistical Characteristics of Energetic Electron Pitch Angle
Distributions in the Van Allen Probe Era: 1. Butterfly Distributions with
Flux Peaks at Preferred Pitch Angles**

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25 **Contents of this file**

26

27 Figures S1 to S29

28 **Introduction**

29 Figure S1 shows the L^* values derived at local pitch angles of 90° , 35° and 0° along the
30 orbital path of Van Allen Probe A during three geomagnetic storms. These results
31 illustrate that below $L^*\sim 5$ (derived at a local pitch angle of 90°) the L^* values are in
32 general not strong functions of pitch angle.

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34 Figure S2 panels (a) and (b) show an example of symmetric PAD fits derived using even
35 Legendre coefficients which have a greater magnitude than the consecutive odd
36 coefficients. Panels (c) and (d) show an example of an asymmetric PAD fit derived from
37 Legendre coefficients, where $|C_2| < |C_3|$ and $|C_6| < |C_7|$. These results illustrate how the
38 asymmetry in the PAD fits can be quantified by comparing the magnitude of the
39 consecutive even and odd Legendre coefficients to identify highly asymmetric PADs
40 likely resulting from errors in the flux measurements.

41 Figure S3 shows how the dip size, DS , of the butterfly pitch angle distributions (PADs)
42 change as a function of the flux integrated over all equatorial pitch angle look directions,
43 $J(\alpha_{eq})$, at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ during time intervals with $Dst=-30 \pm 15$ nT.

44 Figures S4, S5, S6 and S7 also show similar results during $Dst=-60 \pm 15$ nT and $Dst=0$
45 ± 15 nT time intervals at $L^*=3.0, 3.5, 4.0, 4.5$ and 5.0 ± 0.25 . These results are a
46 supplement to the $Dst=-30 \pm 15$ results at $L^*=3.0, 4.0$ and 5.0 ± 0.25 presented in the main
47 paper shown in Figure 7. These supporting Figures are in the same format as the results
48 shown in Figure 7 and show that even during different levels of geomagnetic activity the
49 butterfly PAD dip size, DS , of electrons in the outer radiation belt is generally smaller at
50 higher total flux values integrated over all equatorial look directions, $J(\alpha_{eq})$.

51 Figure S8 shows the correlation between the flux at $\sim 35^\circ$ and $\sim 90^\circ$ for both butterfly and
52 non-butterfly PADs at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ during time intervals with $Dst=-$
53 30 ± 15 nT. Figures S9, S10, S11 and S12 also show similar results during $Dst=-60 \pm 15$
54 nT and $Dst=0 \pm 15$ nT time intervals at $L^*=3.0, 3.5, 4.0, 4.5$ and 5.0 ± 0.25 . These results
55 are a supplement to the $Dst=-30 \pm 15$ nT at $L^*=3.0, 4.0$ and 5.0 ± 0.25 presented in the
56 main paper shown in Figure 8. All these results are in the same format and show that the
57 electron flux in the outer radiation belt at these equatorial pitch angles remains correlated
58 at each level of geomagnetic activity, even as the flux intensity changes by up to 4 orders
59 of magnitude.

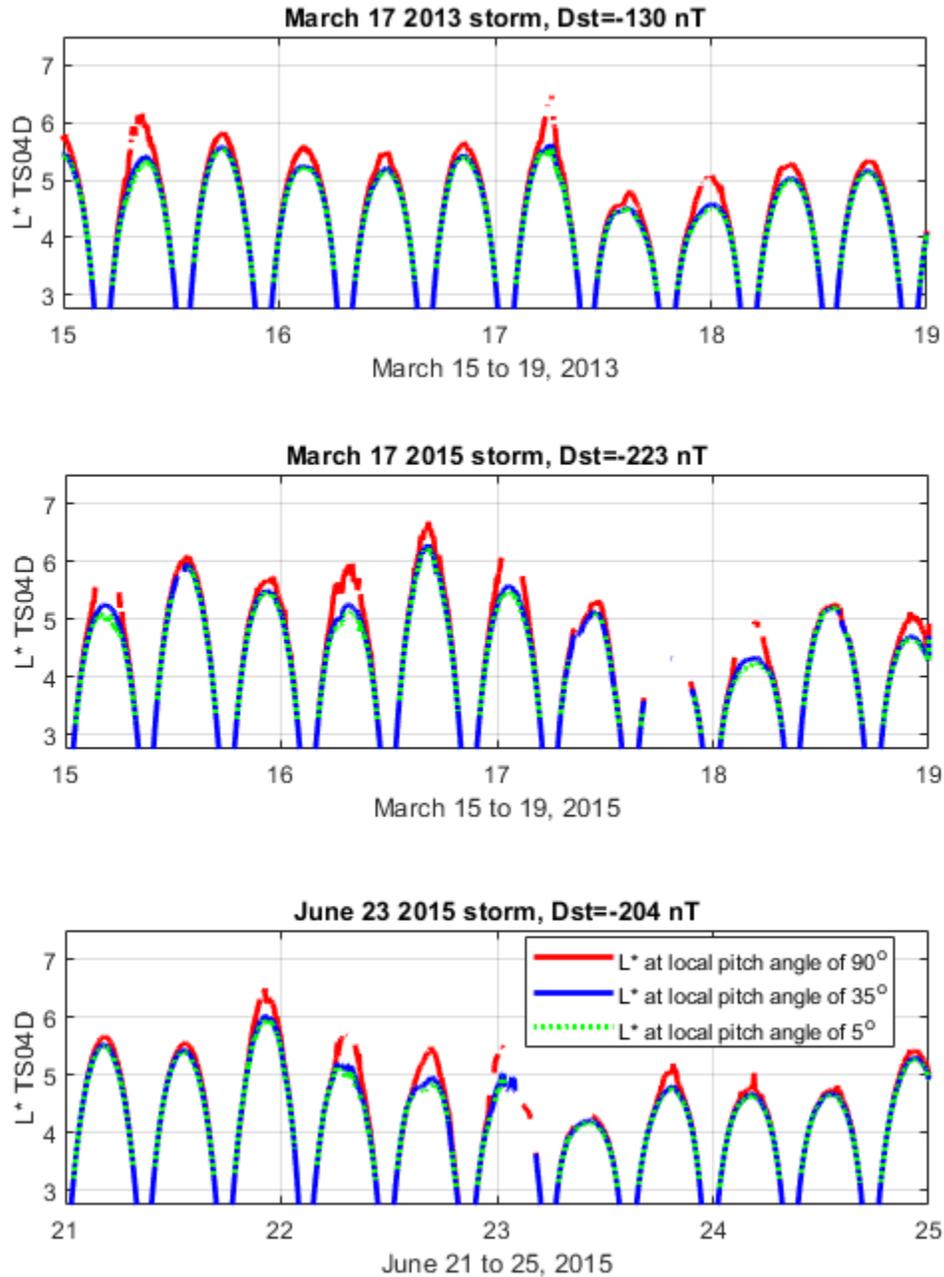
60 Figure S13 shows the ratio between the flux at $\sim 35^\circ$ and $\sim 90^\circ$ for both butterfly and non-
61 butterfly PADs at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ during time intervals with $Dst=-30$
62 ± 15 nT. Figures S14, S15, S16 and S17 also show similar results during $Dst=-60 \pm 15$ nT
63 and $Dst=0 \pm 15$ nT time intervals at $L^*=3.0, 3.5, 4.0, 4.5$ and 5.0 ± 0.25 . These results are

64 a supplement to the $Dst = -30 \pm 15$ nT at $L^* = 3.0, 4.0$ and 5.0 ± 0.25 presented in the main
65 paper shown in Figure 9. All these results are in the same format and illustrate that the
66 flux ratios change with L-shell and electron energy in the same way during each level of
67 geomagnetic activity.

68 Figures S18, S19, S20, S21, S22 and S23 show the correlation between the flux at $\sim 65^\circ$
69 and $\sim 90^\circ$ for both butterfly and non-butterfly PADs, during intervals with $Dst = -60 \pm 15$
70 nT, $Dst = -30 \pm 15$ nT and $Dst = 0 \pm 15$ nT at $L^* = 3.0, 3.5, 4.0, 4.5$ and 5.0 ± 0.25 . These
71 results are a supplement to the results presented in the main paper shown in Figure 8 and
72 are in the same format as the results presented in Figures 8 in the main paper, as well as
73 Figures S12, S13, S14, S15 and S16, showing that the flux at equatorial pitch angles of
74 $\sim 65^\circ$ and $\sim 90^\circ$ remains highly correlated during each level of geomagnetic activity, even
75 as the flux intensity changes by up to 4 orders of magnitude.

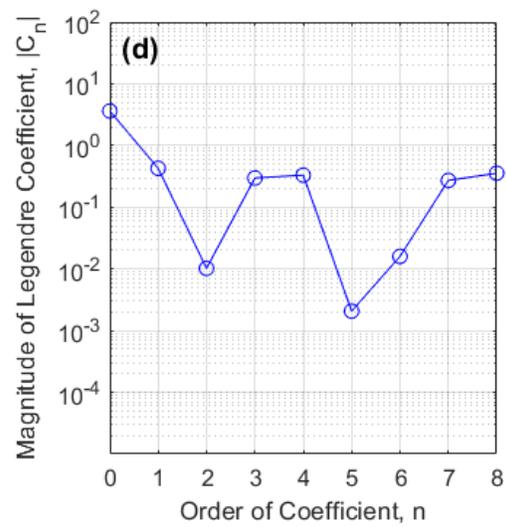
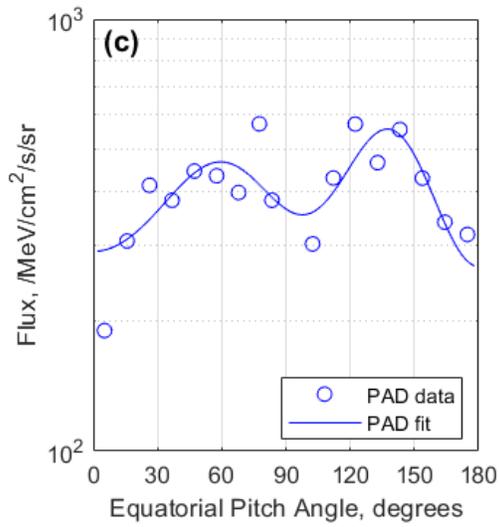
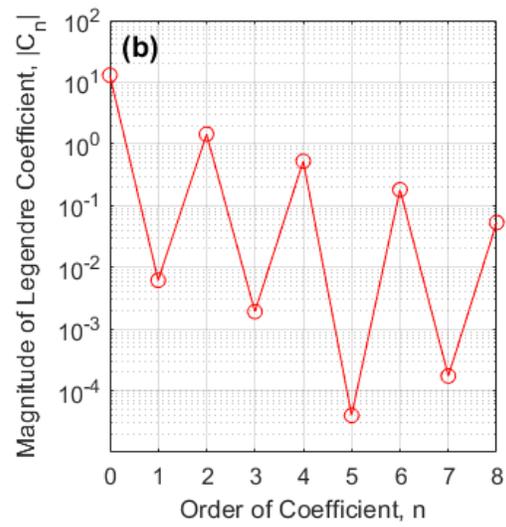
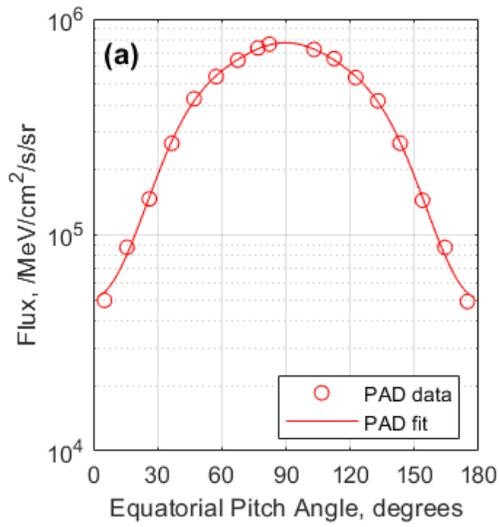
76 Figures S24, S25, S26, S27, S28 and S29 show the ratio between the flux at $\sim 65^\circ$ and
77 $\sim 90^\circ$ for both butterfly and non-butterfly PADs during intervals with $Dst = -60 \pm 15$ nT,
78 $Dst = -30 \pm 15$ nT and $Dst = 0 \pm 15$ nT at $L^* = 3.0, 3.5, 4.0, 4.5$ and 5.0 ± 0.25 . These results
79 are a supplement to the $Dst = -30 \pm 15$ nT results presented in the main paper shown in
80 Figure 9. All these results are in the same format and illustrate that the flux ratios change
81 with L-shell and electron energy in the same way during different levels of geomagnetic
82 activity.

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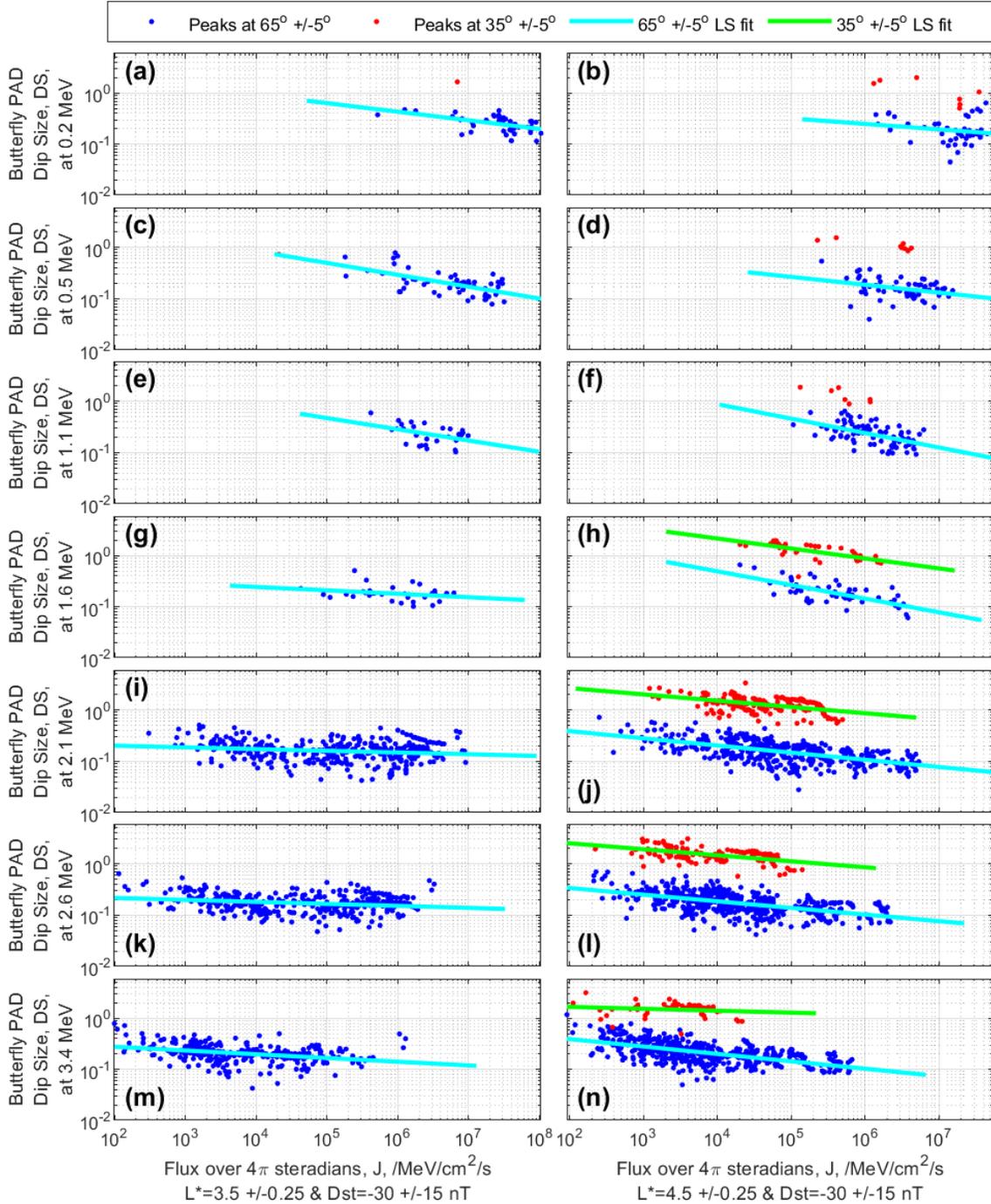
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Figure S1. L^* values derived at local pitch angles of 90° , 35° and 0° along the orbital path of Van Allen Probe A during three geomagnetic storms, illustrating that below $L^* \sim 5$ (derived at a local pitch angle of 90°) the L^* values are in general not strong functions of pitch angle.



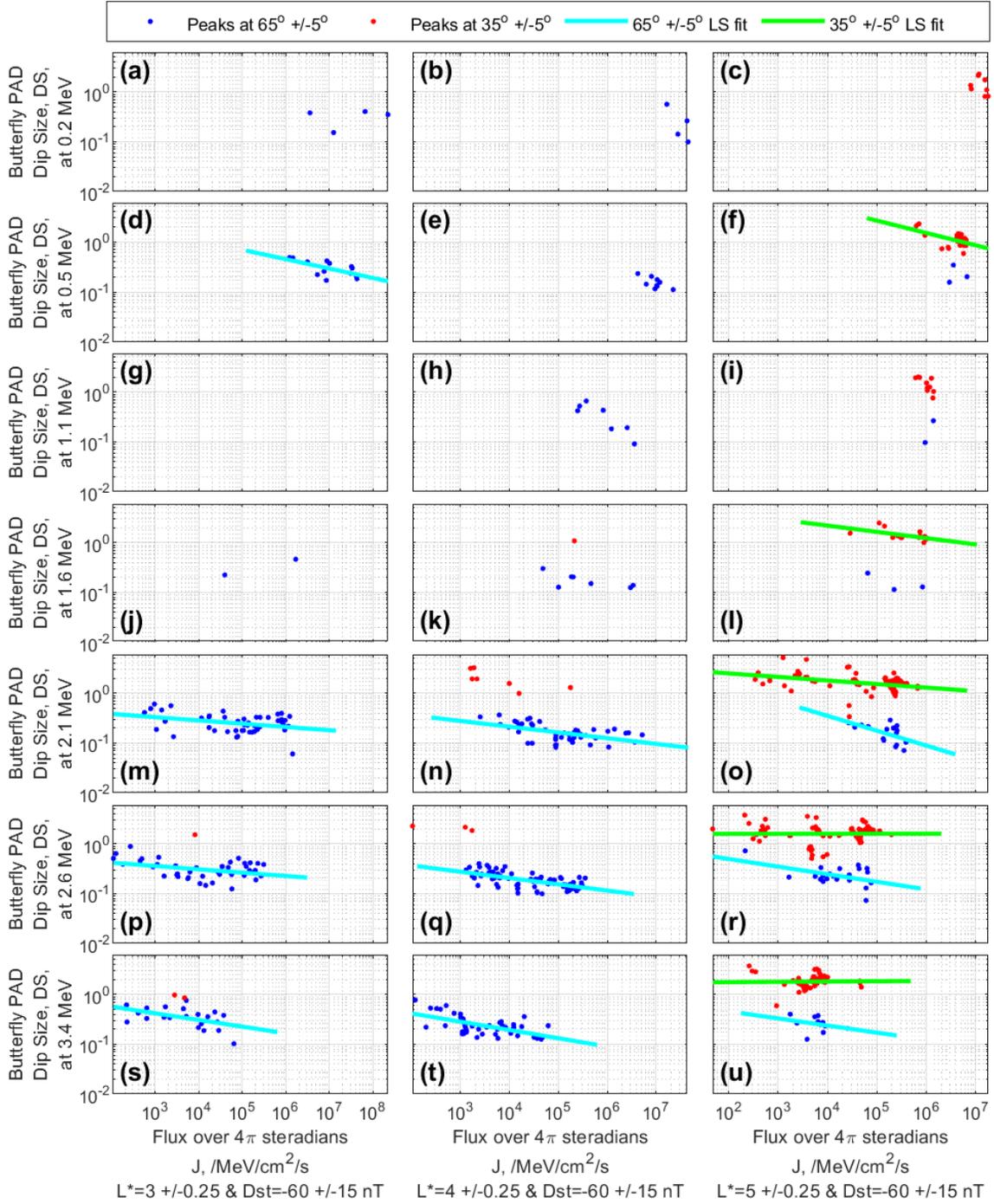
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Figure S2. Panels (a) and (b) show an example of a symmetric PAD fit where the even Legendre polynomials are much greater than the consecutive odd coefficients. Panels (c) and (d) show an example of an asymmetric PAD fit where the even Legendre polynomials are not all greater than the consecutive odd coefficients. For example, $|C_2| < |C_3|$ and $|C_6| < |C_7|$.



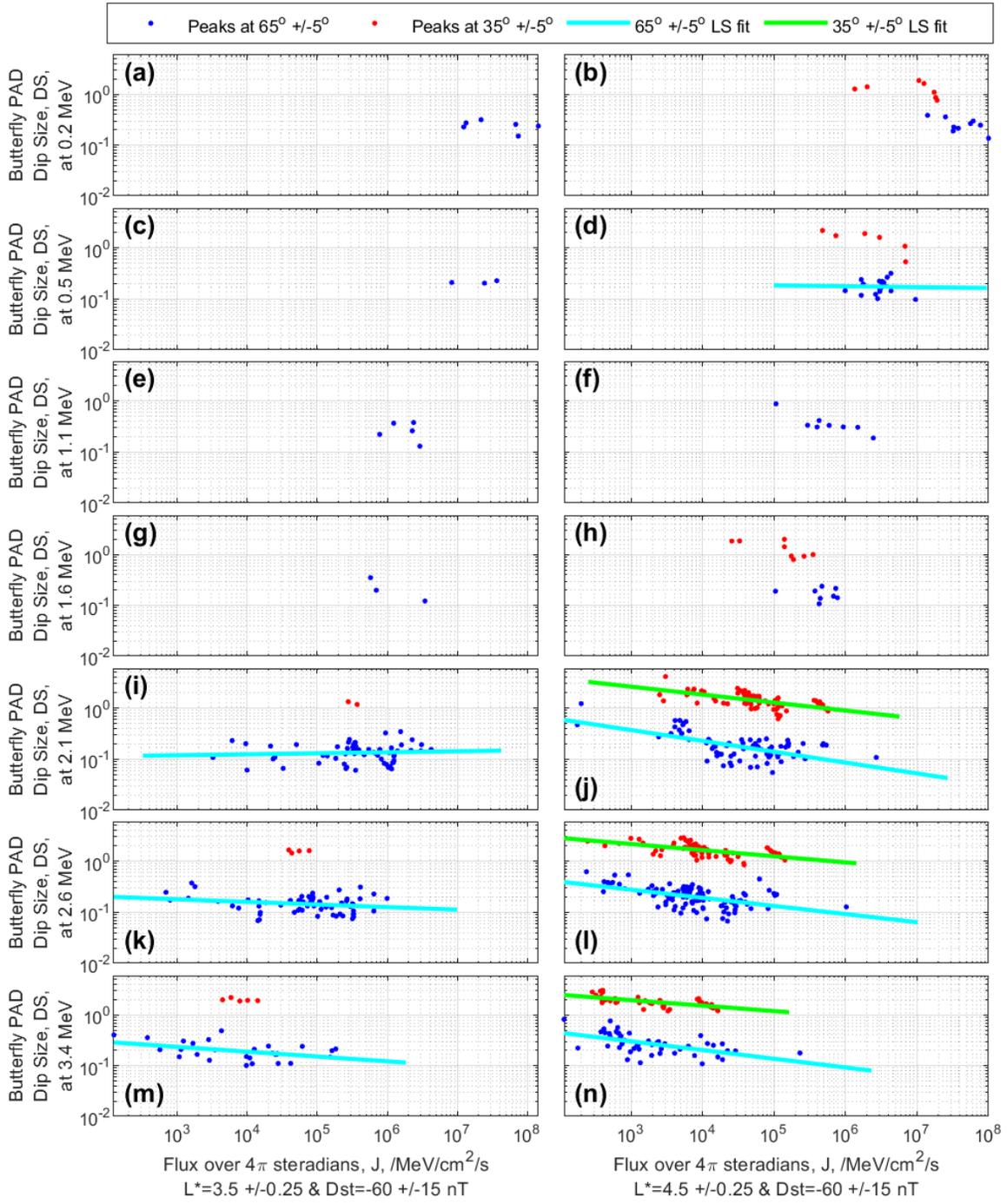
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Figure S3. The dip size, DS , of butterfly PADs as a function of the flux integrated over all equatorial pitch angle look directions, $J(\alpha_{eq})$, at $Dst=-30 \pm 15$ nT for $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ in the same format as the results shown in Figure 7 in the main paper.



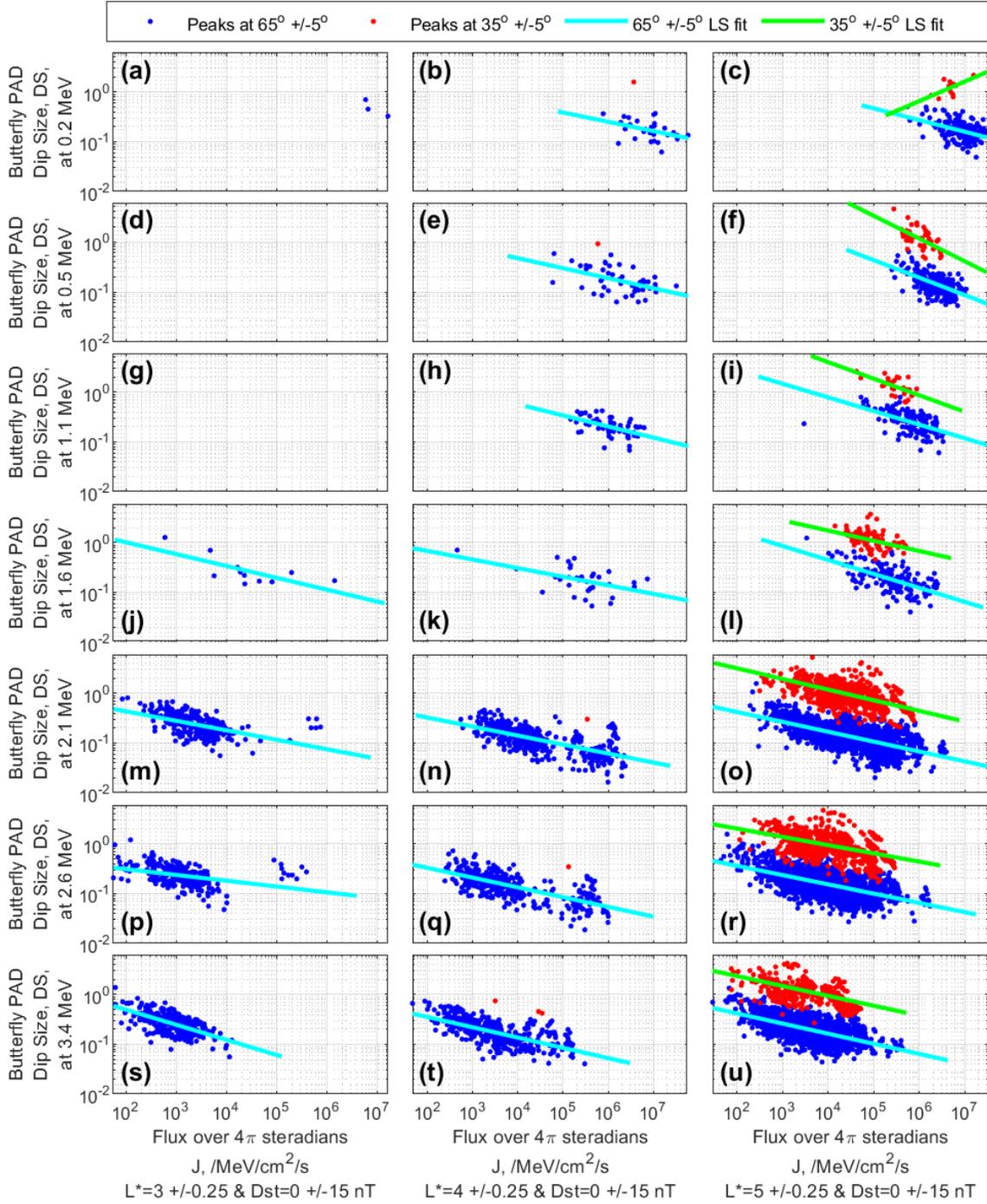
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Figure S4. The dip size, DS , of butterfly PADs as a function of the flux integrated over all equatorial pitch angle look directions, $J(\alpha_{eq})$, for $\text{Dst}=-60 \pm 15$ nT, in the same format as the results shown in Figure 7 in the main paper.



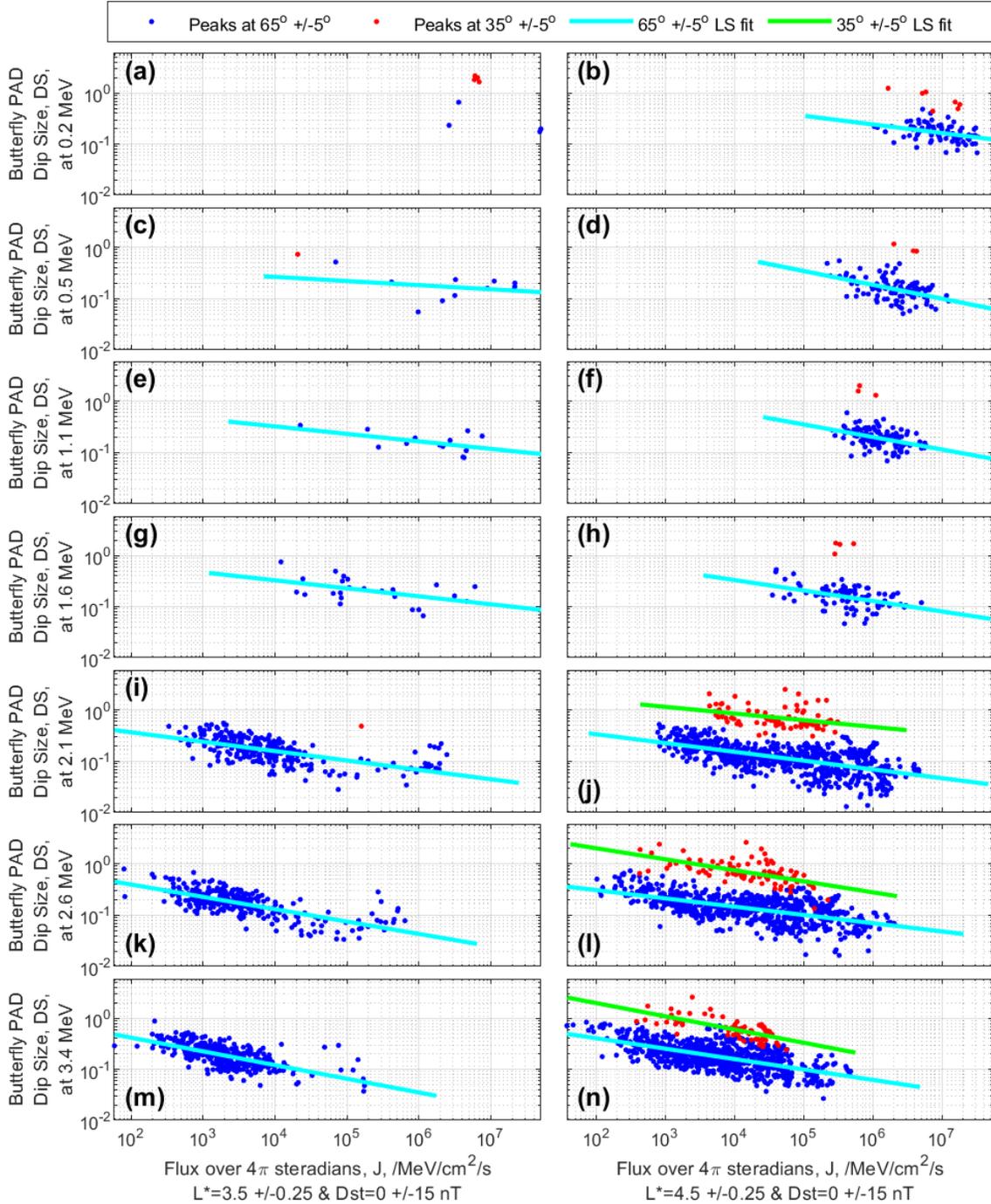
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Figure S5. The dip size, DS , of butterfly PADs as a function of the flux integrated over all equatorial pitch angle look directions, $J(\alpha_{eq})$, at $Dst = -60 \pm 15$ nT for $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in the same format as the results shown in Figure 7 in the main paper.



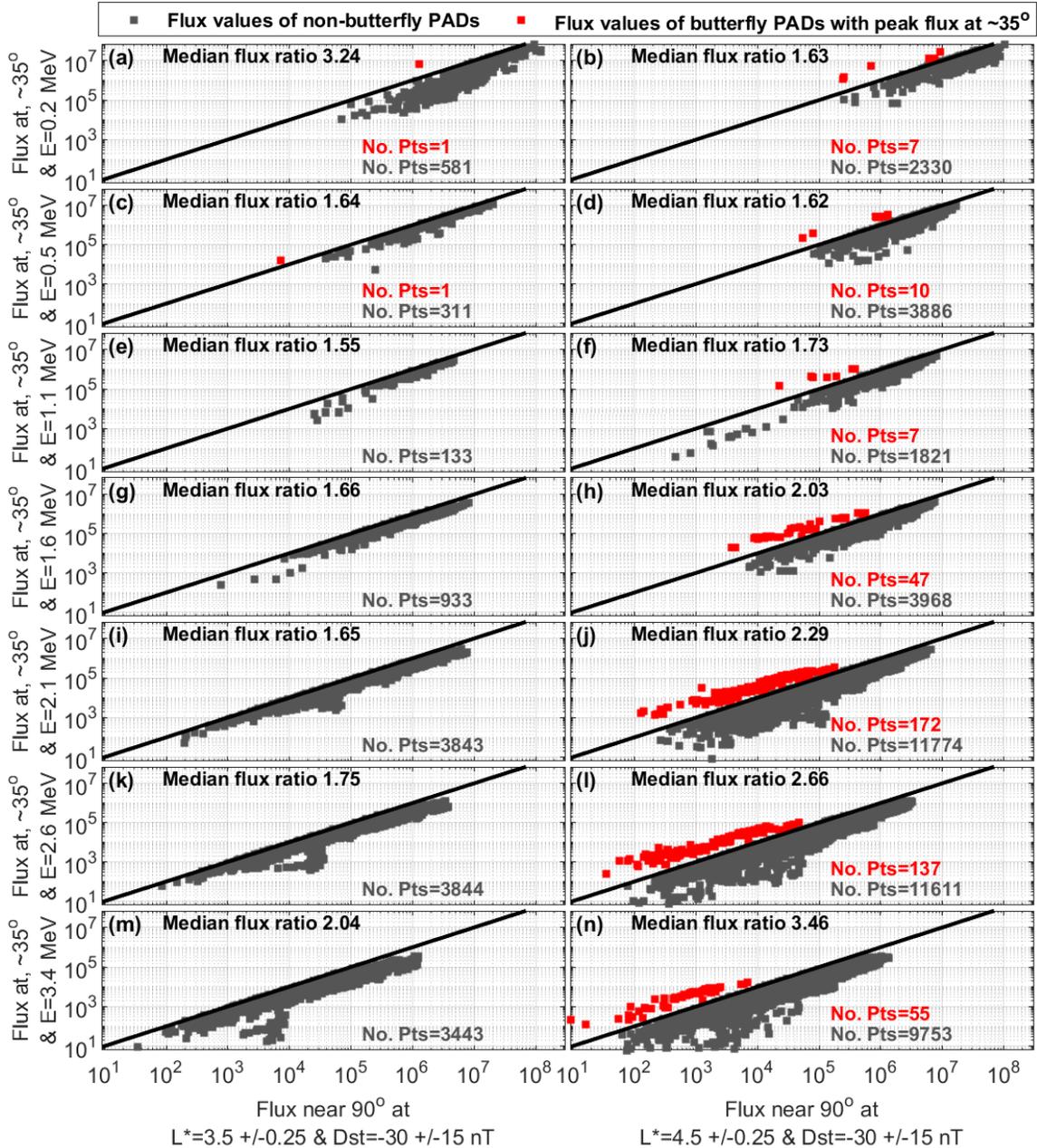
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Figure S6. The dip size, DS , of butterfly PADs as a function of the flux integrated over all equatorial pitch angle look directions, $J(\alpha_{eq})$, for $\text{Dst}=0 \pm 15$ nT, in the same format as the results shown in Figure 7 in the main paper.



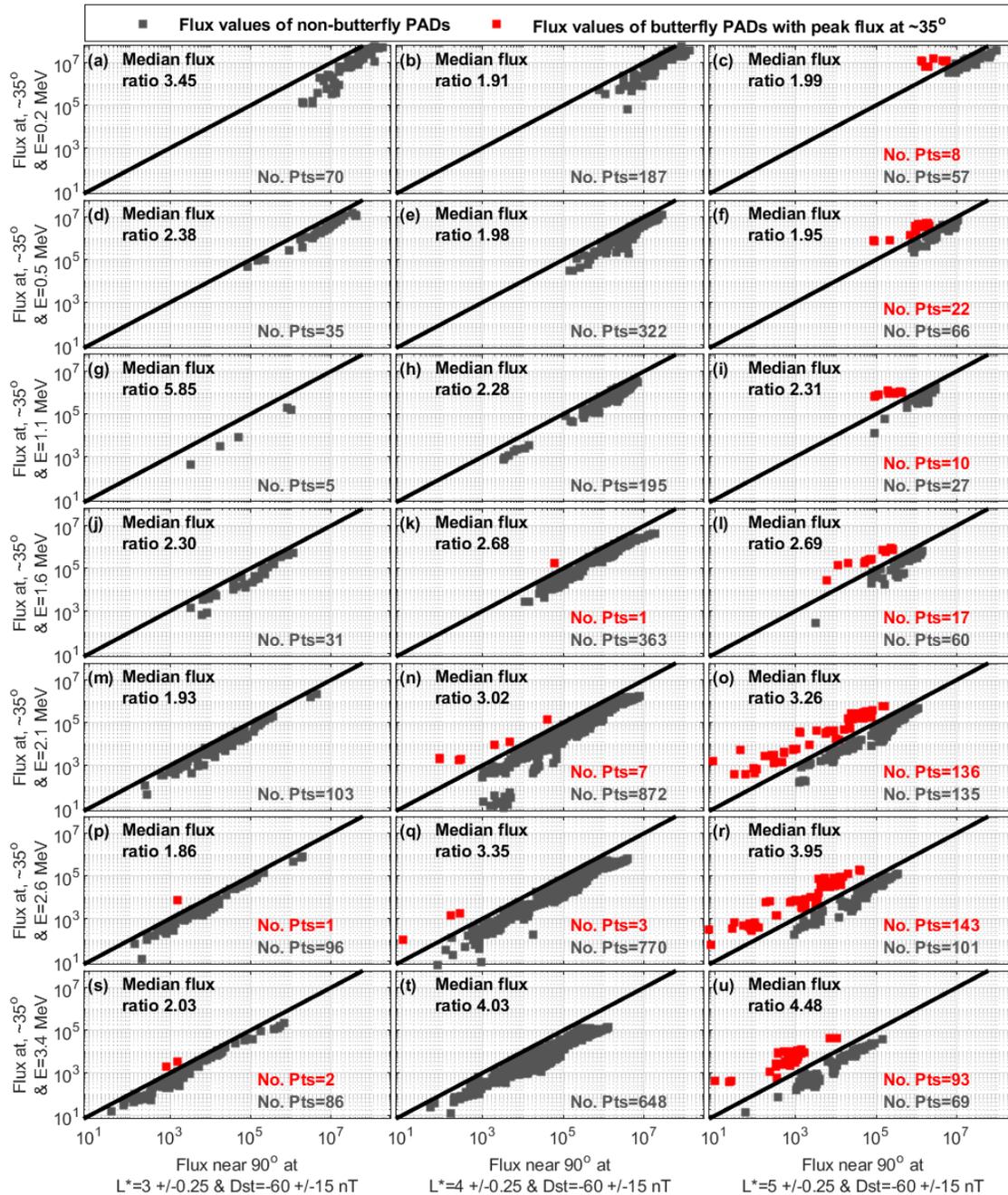
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Figure S7. The dip size, DS , of butterfly PADs as a function of the flux integrated over all equatorial pitch angle look directions, $J(\alpha_{eq})$, at $Dst=0 \pm 15$ nT for $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ in the same format as the results shown in Figure 7 in the main paper.



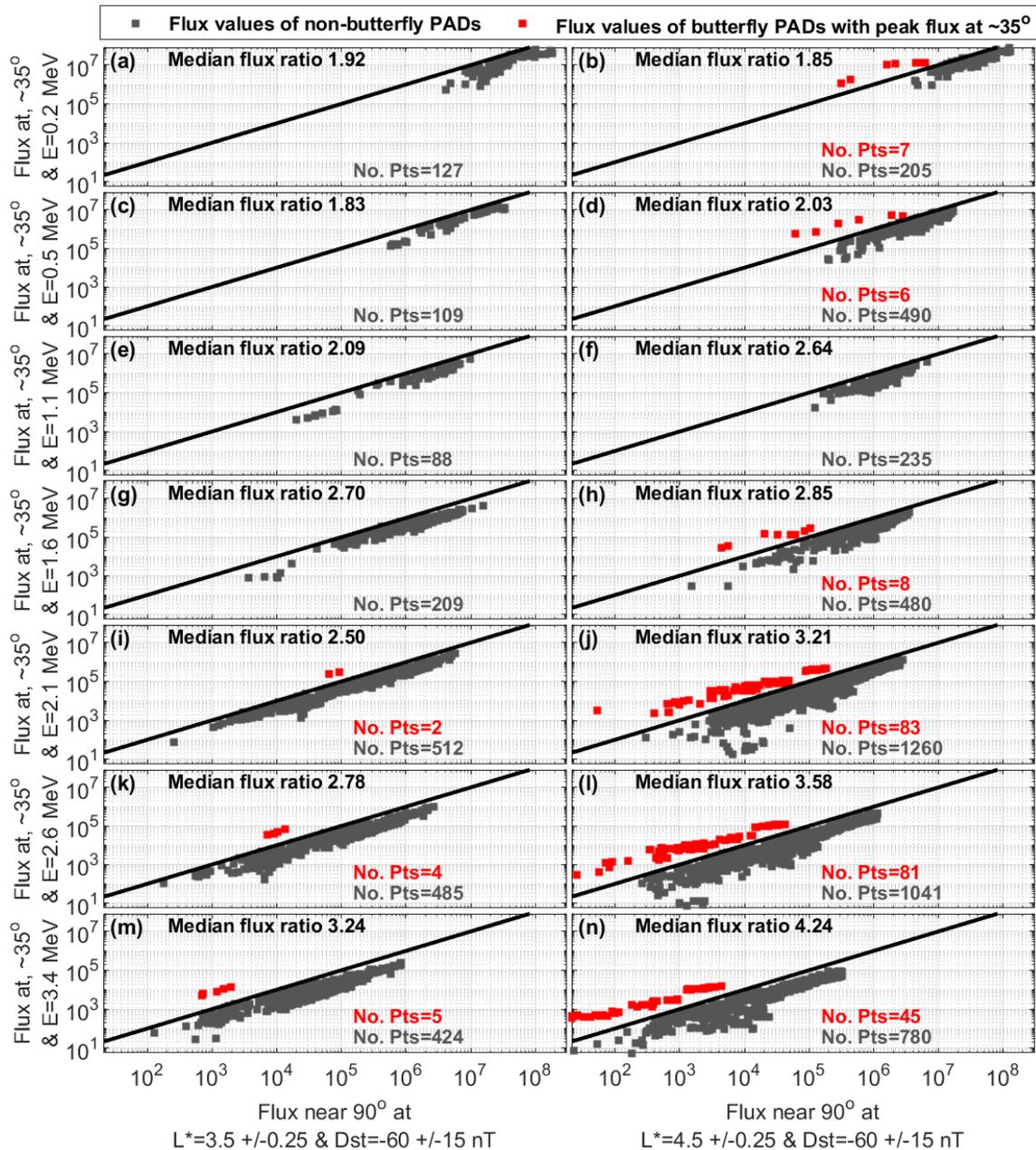
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Figure S8. The red dots indicate results for butterfly PADs that have a peak flux at equatorial pitch angles of $35^\circ \pm 5^\circ$. For these butterfly PADs each data point represents the flux near equatorial pitch angles of 35° , where the flux reaches a peak value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these non-butterfly PADs each data point represents the flux near an equatorial pitch angle of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 35° . Results shown here are for $Dst = -30 \pm 15$ nT at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in a similar format to the results presented in Figure 8 in the main paper.



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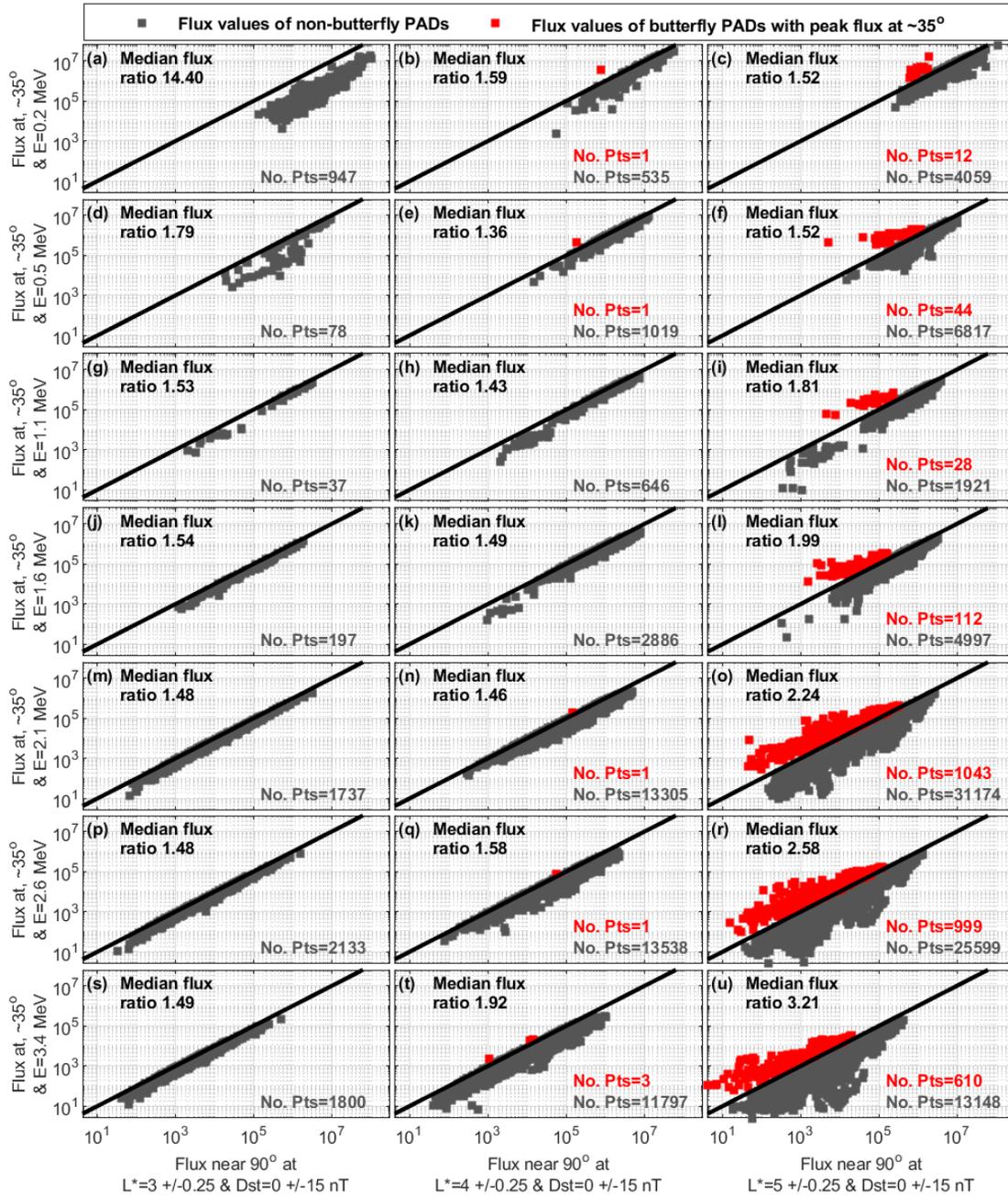
146 **Figure S9.** The red dots indicate results for butterfly PADs that have a peak flux at
 147 equatorial pitch angles of $35^\circ \pm 5^\circ$. For these butterfly PADs each data point
 148 represents the flux near equatorial pitch angles of 35° , where the flux reaches a peak
 149 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 150 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 151 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 152 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 35° .
 153 Results shown here are for $Dst = -60 \pm 15$ nT, in a similar format to the results
 154 presented in Figure 8 in the main paper.



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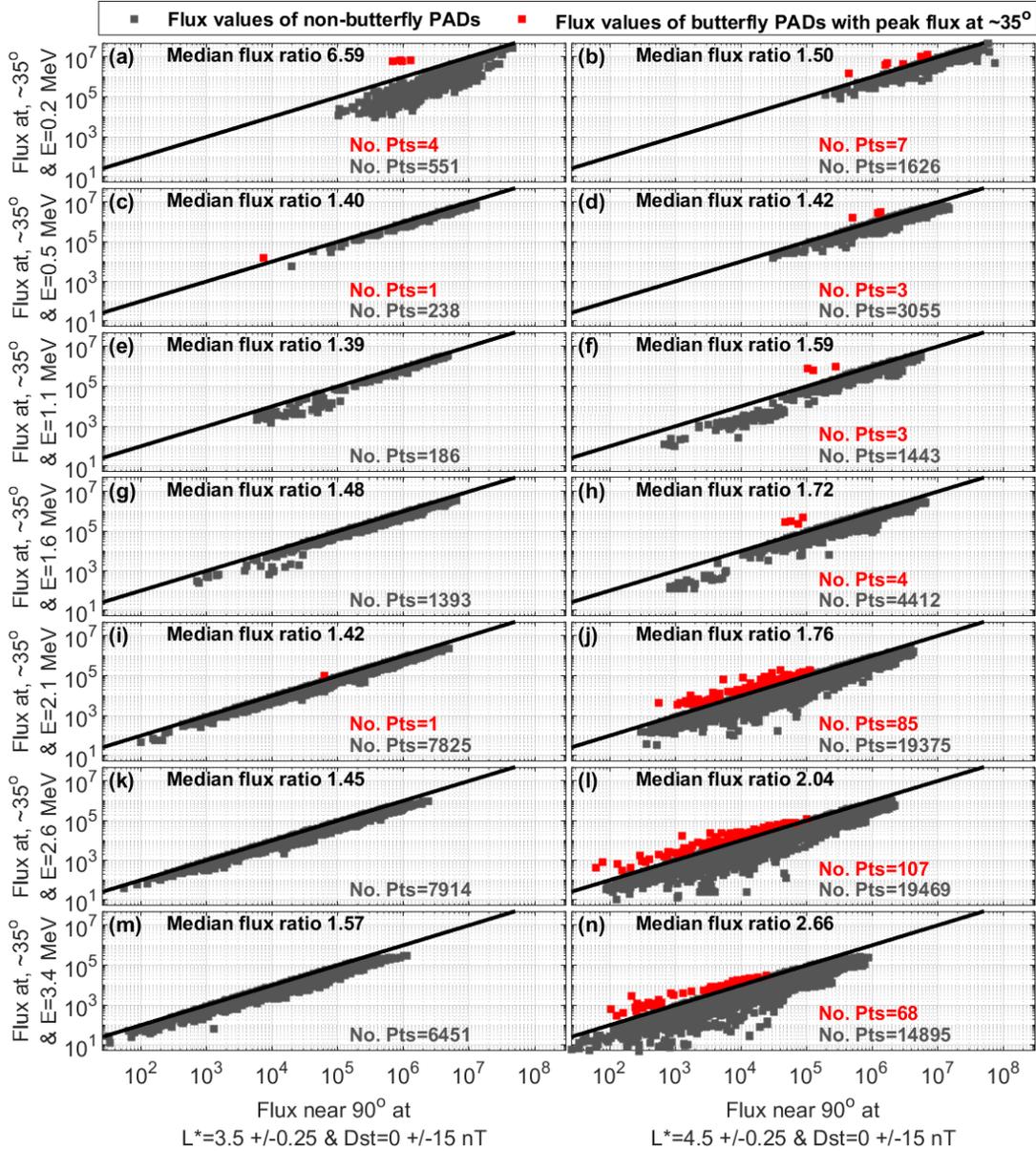
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158 **Figure S10.** The red dots indicate results for butterfly PADs that have a peak flux at
 159 equatorial pitch angles of $35^\circ \pm 5^\circ$. For these butterfly PADs each data point
 160 represents the flux near equatorial pitch angles of 35° , where the flux reaches a peak
 161 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 162 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 163 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 164 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 35° .
 165 Results shown here are for $Dst=-60 \pm 15$ nT at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ in a
 166 similar format to the results presented in Figure 8 in the main paper.



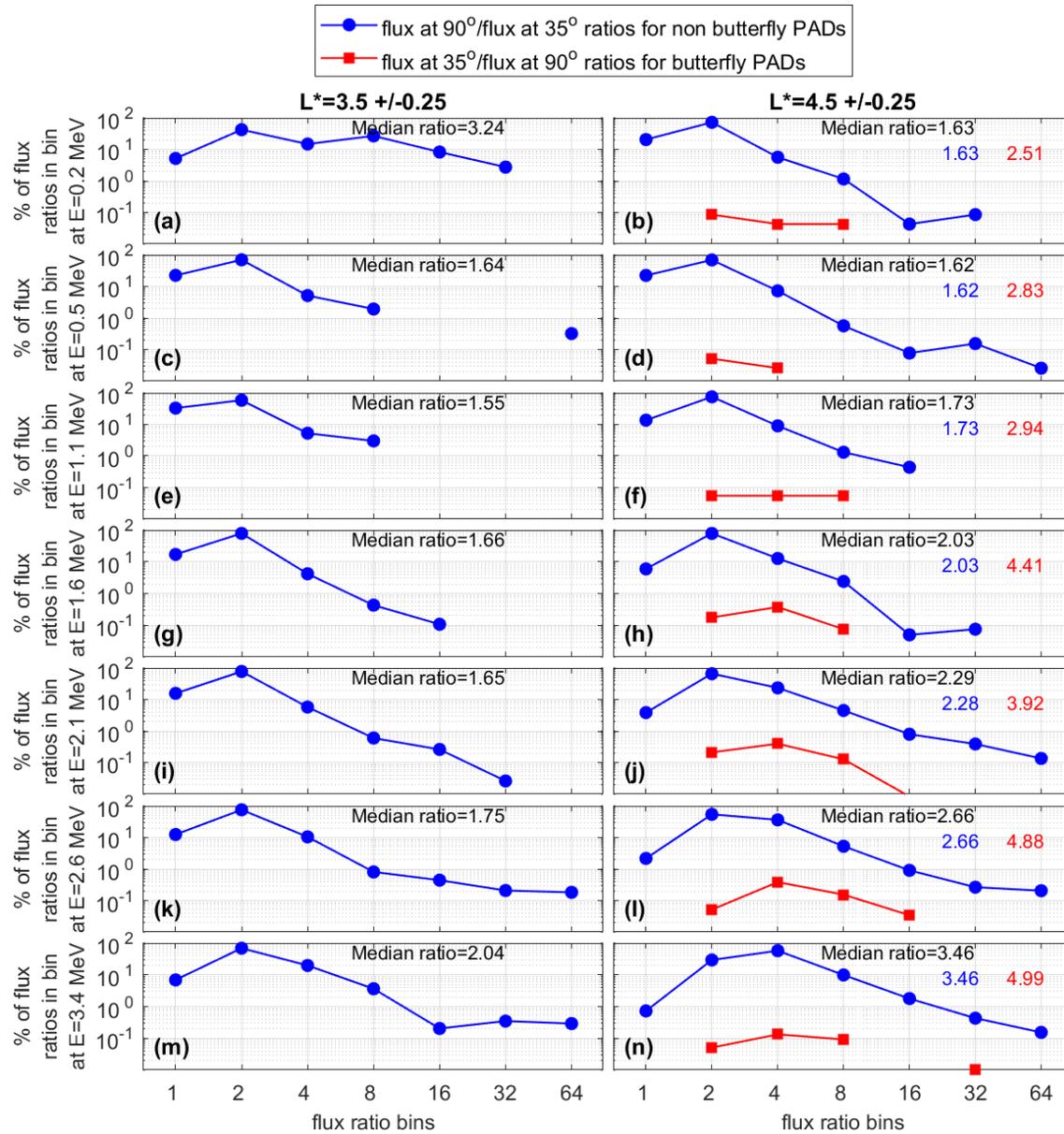
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Figure S11. The red dots indicate results for butterfly PADS that have a peak flux at equatorial pitch angles of $35^\circ \pm 5^\circ$. For these butterfly PADS each data point represents the flux near equatorial pitch angles of 35° , where the flux reaches a peak value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local minimum. Similarly, the gray dots indicate results for non-butterfly PADS. For these non-butterfly PADS each data point represents the flux near an equatorial pitch angle of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 35° . Results shown here are for $Dst=0 \pm 15$ nT, in a similar format to the results presented in Figure 8 in the main paper.



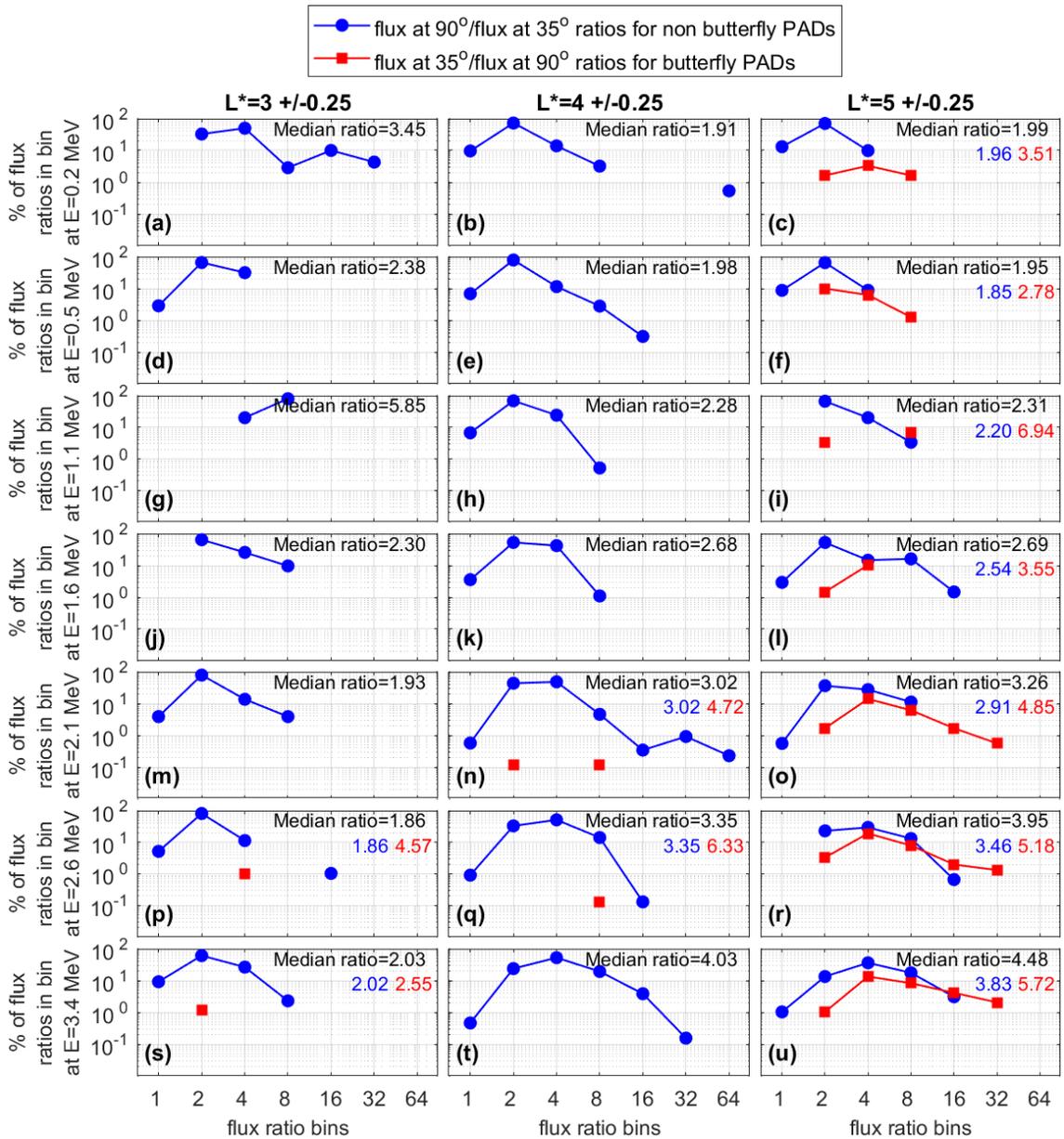
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Figure S12. The red dots indicate results for butterfly PADs that have a peak flux at equatorial pitch angles of $35^\circ \pm 5^\circ$. For these butterfly PADs each data point represents the flux near equatorial pitch angles of 35° , where the flux reaches a peak value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these non-butterfly PADs each data point represents the flux near an equatorial pitch angle of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 35° . Results shown here are for $Dst=0 \pm 15$ nT at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ in a similar format to the results presented in Figure 8 in the main paper.

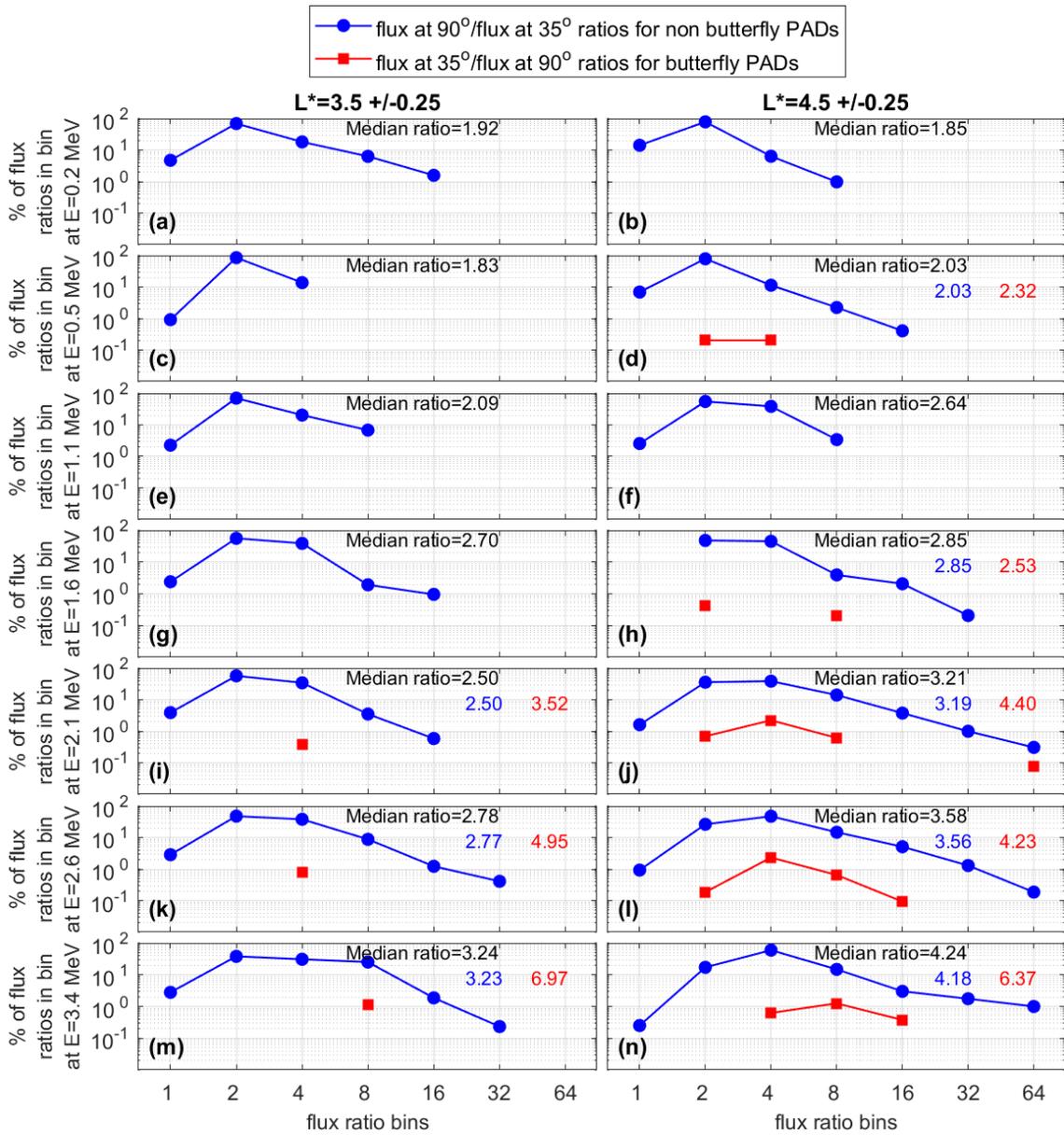


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Figure S13. The curves indicate how the flux values at equatorial pitch angles of $\sim 35^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -30 \text{ nT} \pm 15 \text{ nT}$ at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in the same format as the results presented in Figure 9 in the main paper.

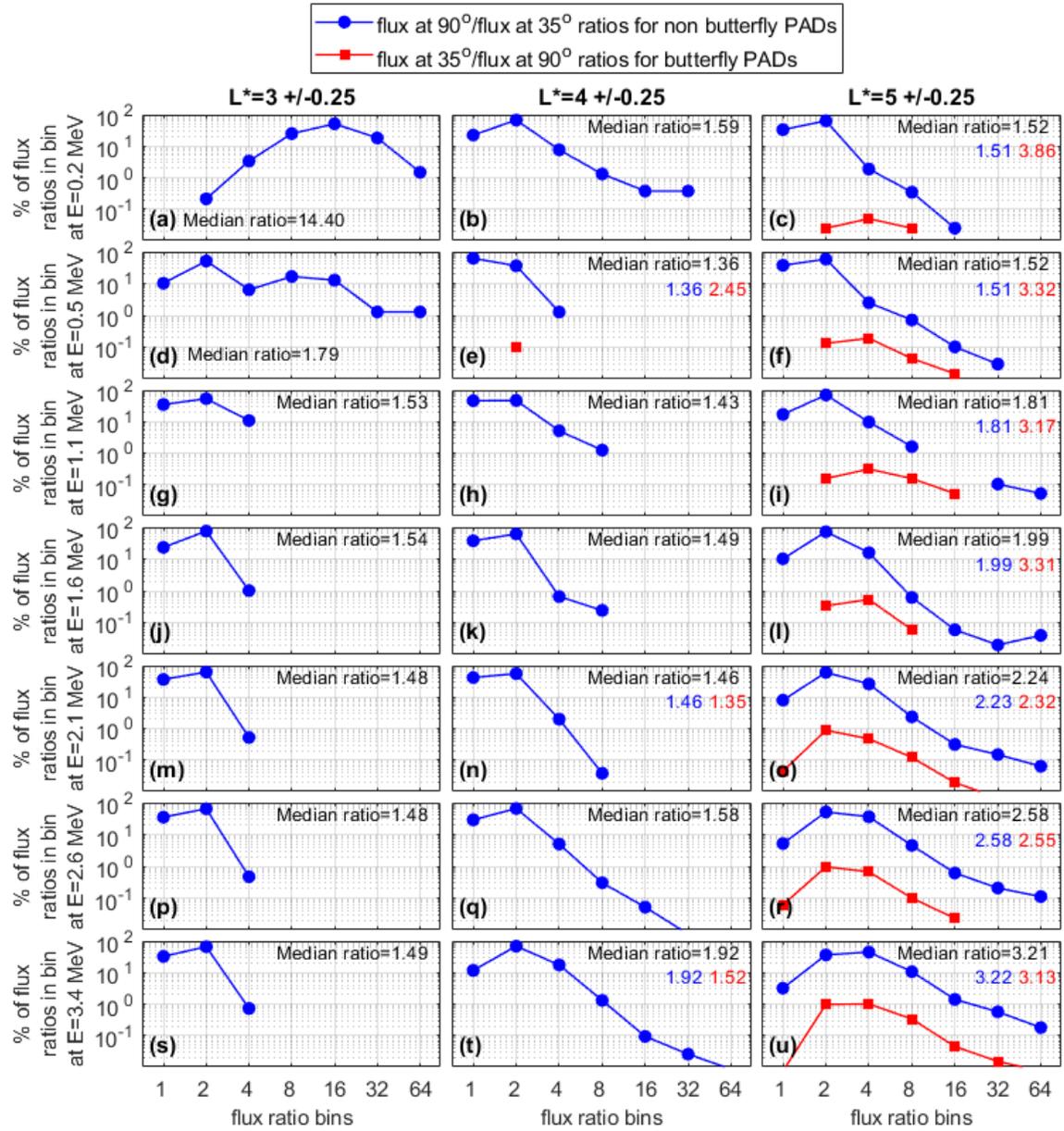


210 **Figure S14.** The curves indicate how the flux values at equatorial pitch angles of $\sim 35^\circ$
 211 and $\sim 90^\circ$ differ. These results are for $Dst = -60 \text{ nT} \pm 15 \text{ nT}$, in the same format as the
 212 results presented in Figure 9 in the main paper.
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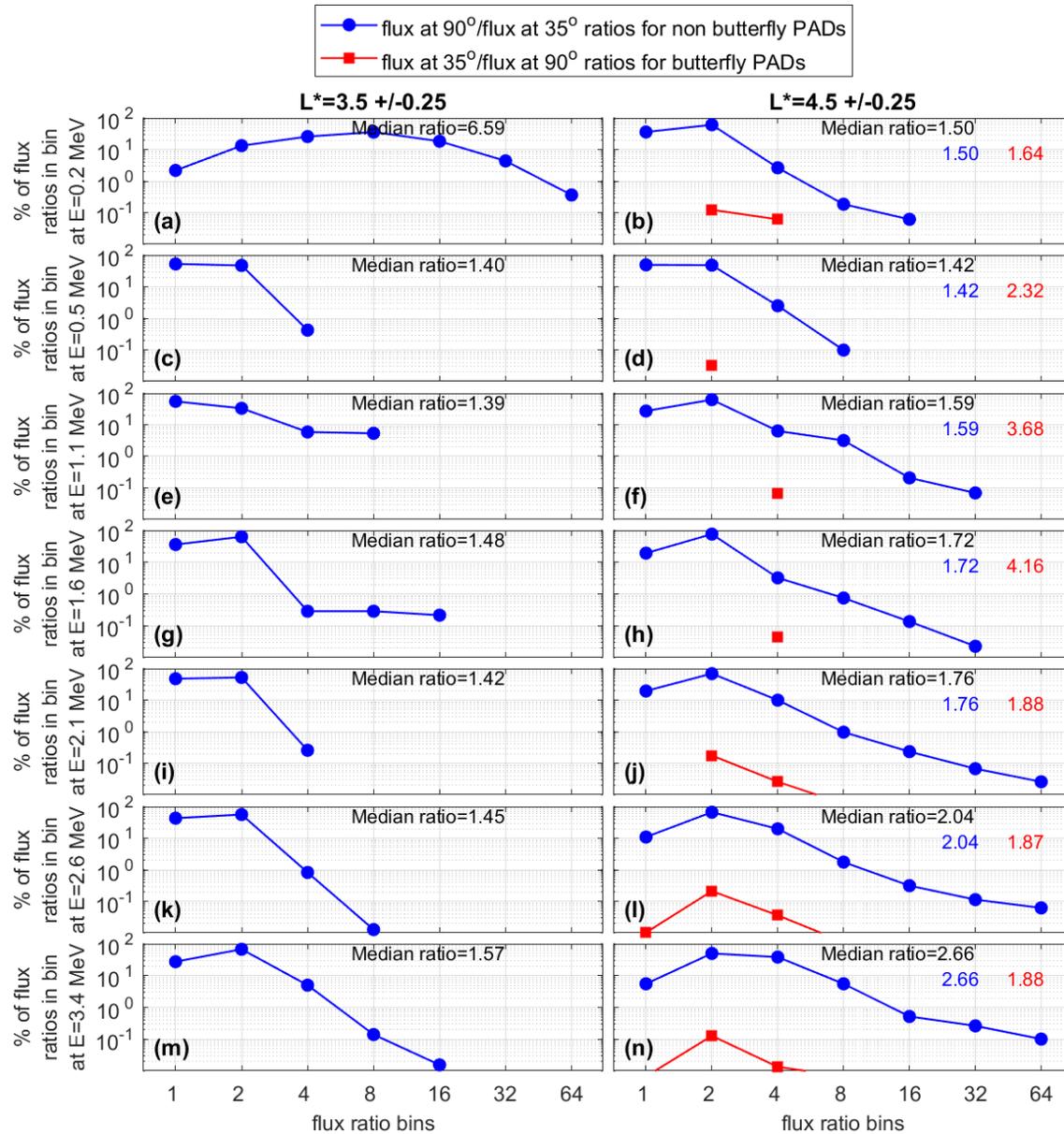
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Figure S15. The curves indicate how the flux values at equatorial pitch angles of $\sim 35^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -60 \text{ nT} \pm 15 \text{ nT}$ at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in the same format as the results presented in Figure 9 in the main paper.



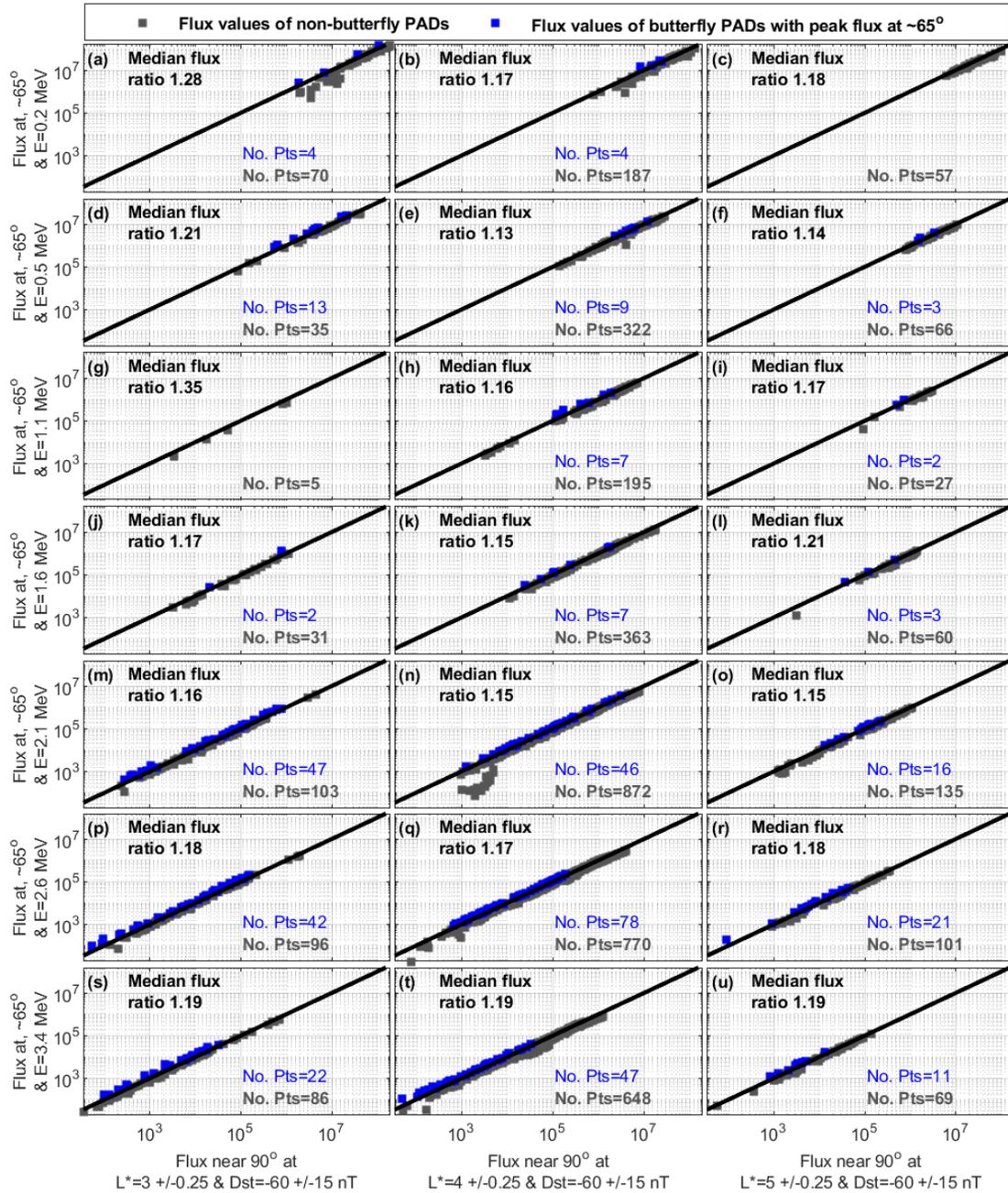
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Figure S16. The curves indicate how the flux values at equatorial pitch angles of $\sim 35^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst=0 \text{ nT} \pm 15 \text{ nT}$, in the same format as the results presented in Figure 9 in the main paper.



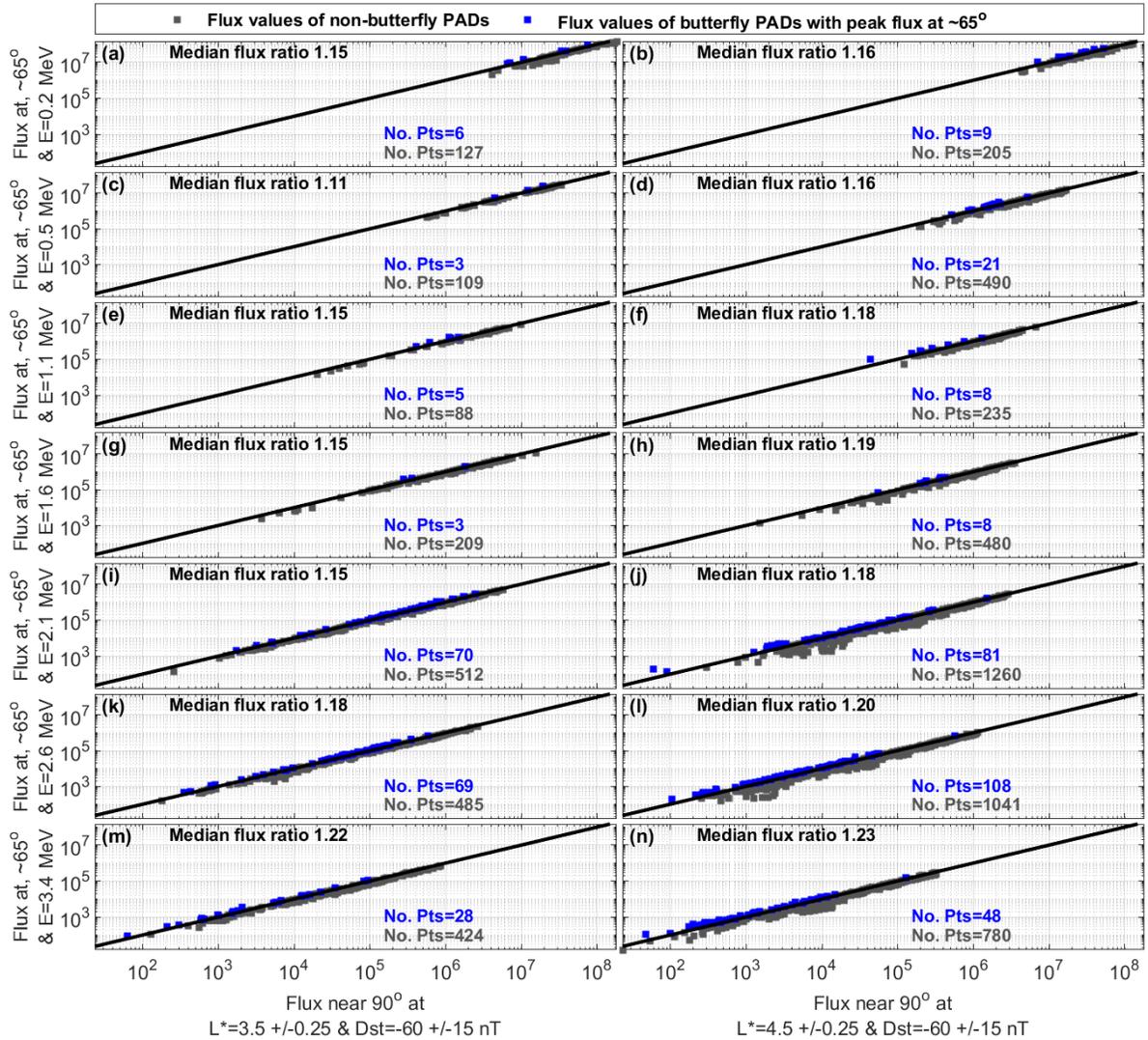
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Figure S17. The curves indicate how the flux values at equatorial pitch angles of $\sim 35^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst=0 \text{ nT} \pm 15 \text{ nT}$ at $L^*=3.5 \pm 0.25$ and $L^*=4.5 \pm 0.25$ in the same format as the results presented in Figure 9 in the main paper.



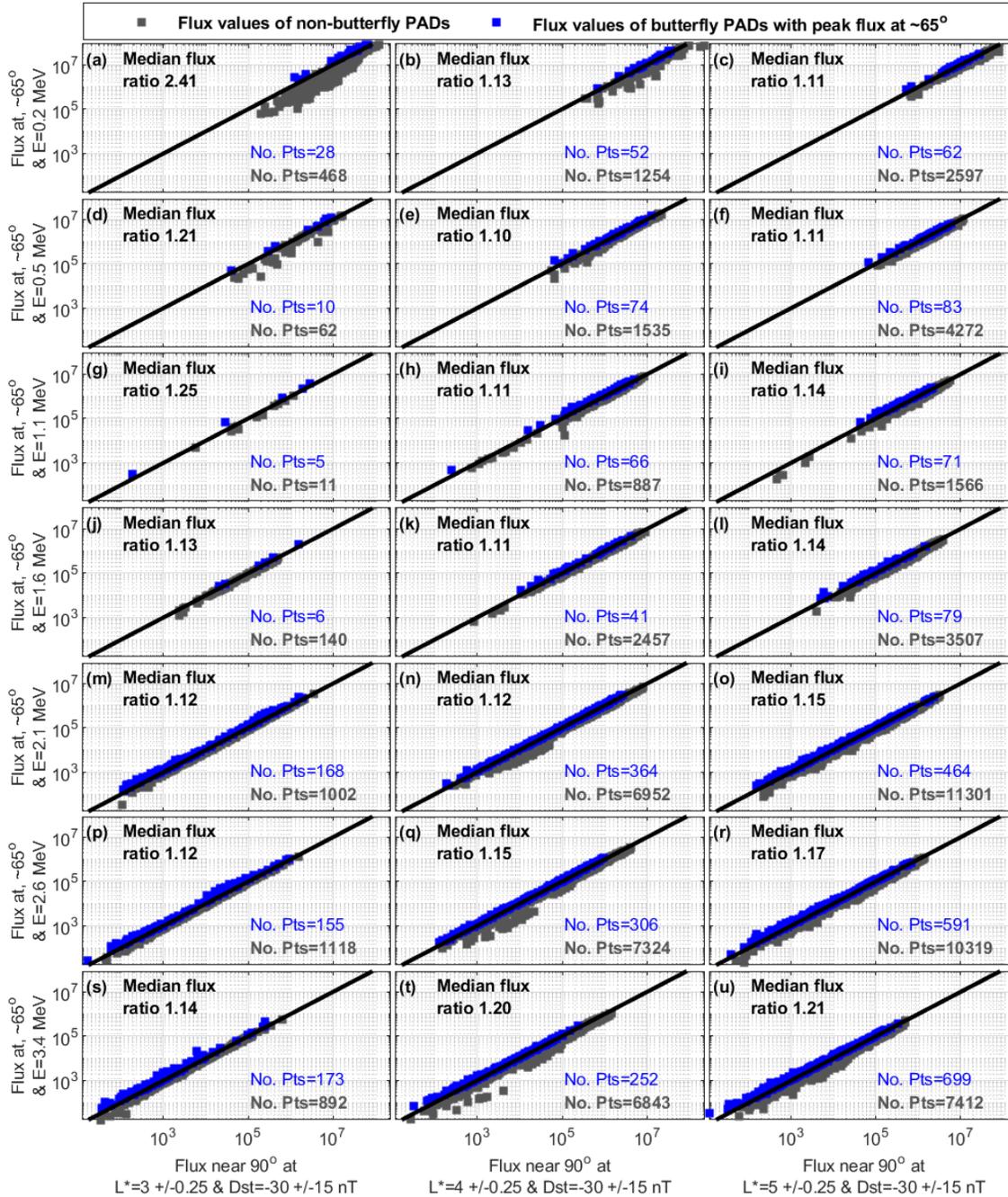
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239 **Figure S18.** The blue dots indicate results for butterfly PADs that have a peak flux at
 240 equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point
 241 represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak
 242 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 243 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 244 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 245 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° .
 246 Results shown here are for $Dst = -60 \pm 15$ nT, in a similar format to the results
 247 presented in Figure 8 in the main paper.
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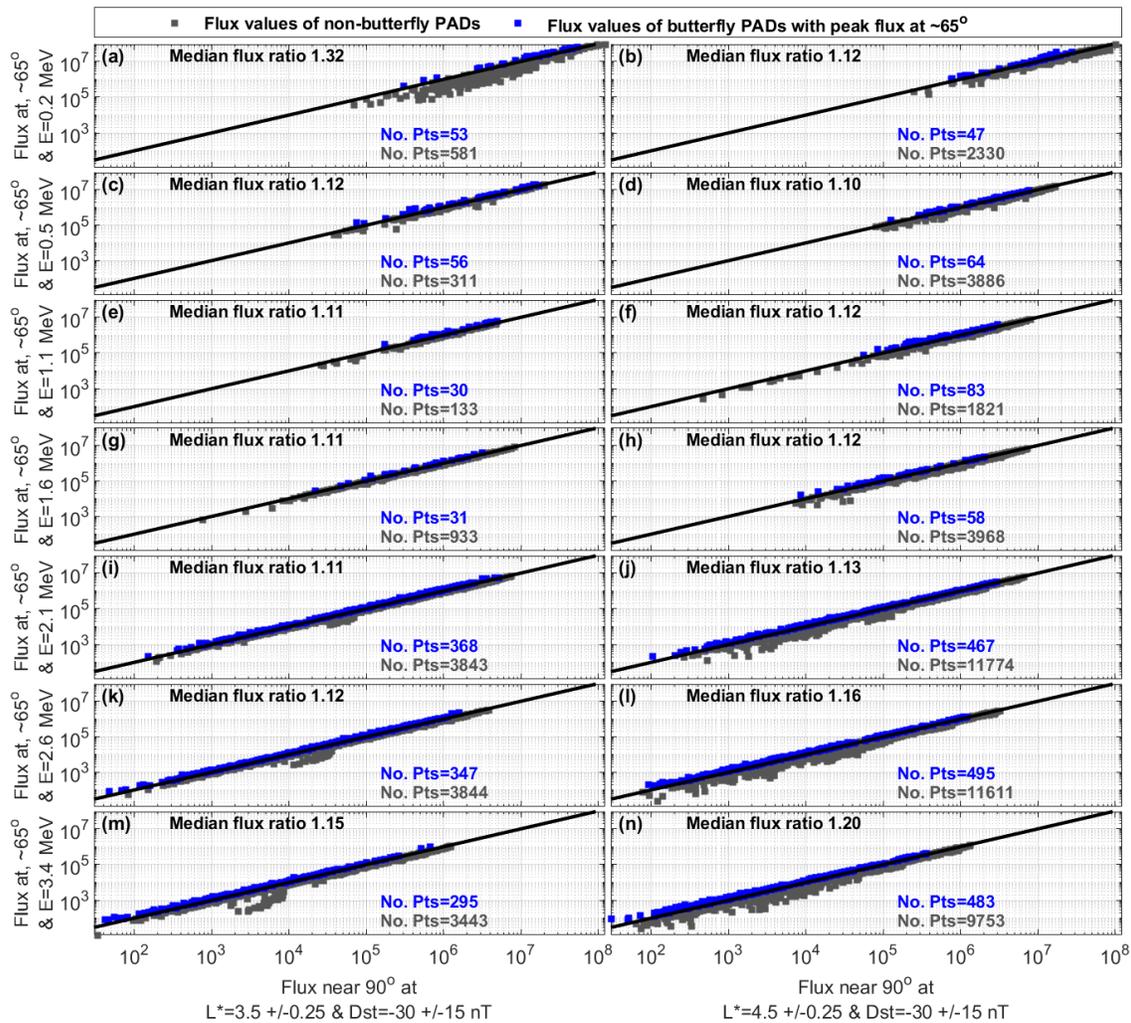
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Figure S19. The blue dots indicate results for butterfly PADs that have a peak flux at equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these non-butterfly PADs each data point represents the flux near an equatorial pitch angle of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° . Results shown here are for $Dst = -60 \pm 15$ nT at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in a similar format to the results presented in Figure 8 in the main paper.



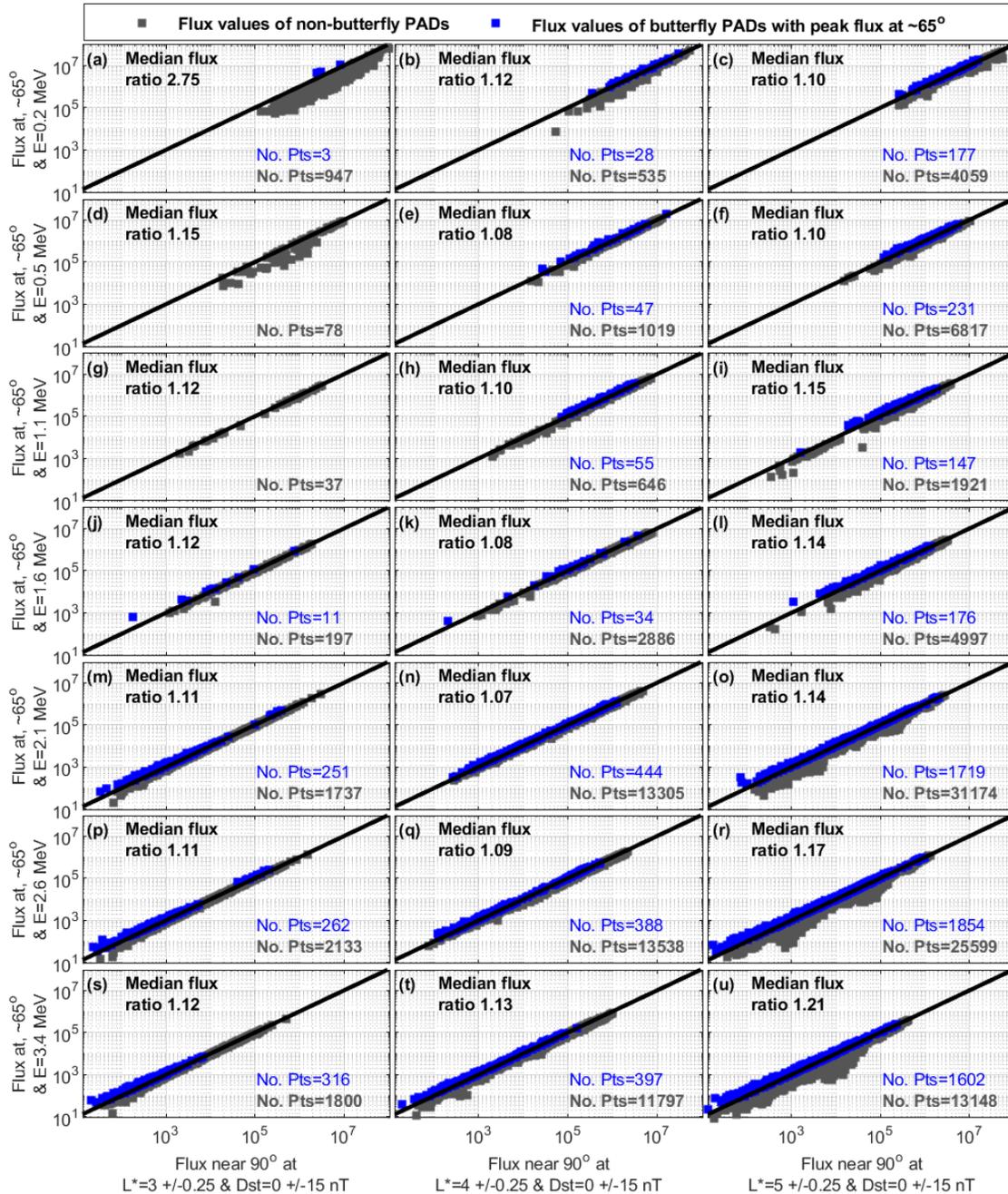
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264 **Figure S20.** The blue dots indicate results for butterfly PADs that have a peak flux at
 265 equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point
 266 represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak
 267 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 268 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 269 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 270 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° .
 271 Results shown here are for $Dst=-30 \pm 15$ nT, in a similar format to the results
 272 presented in Figure 8 in the main paper.



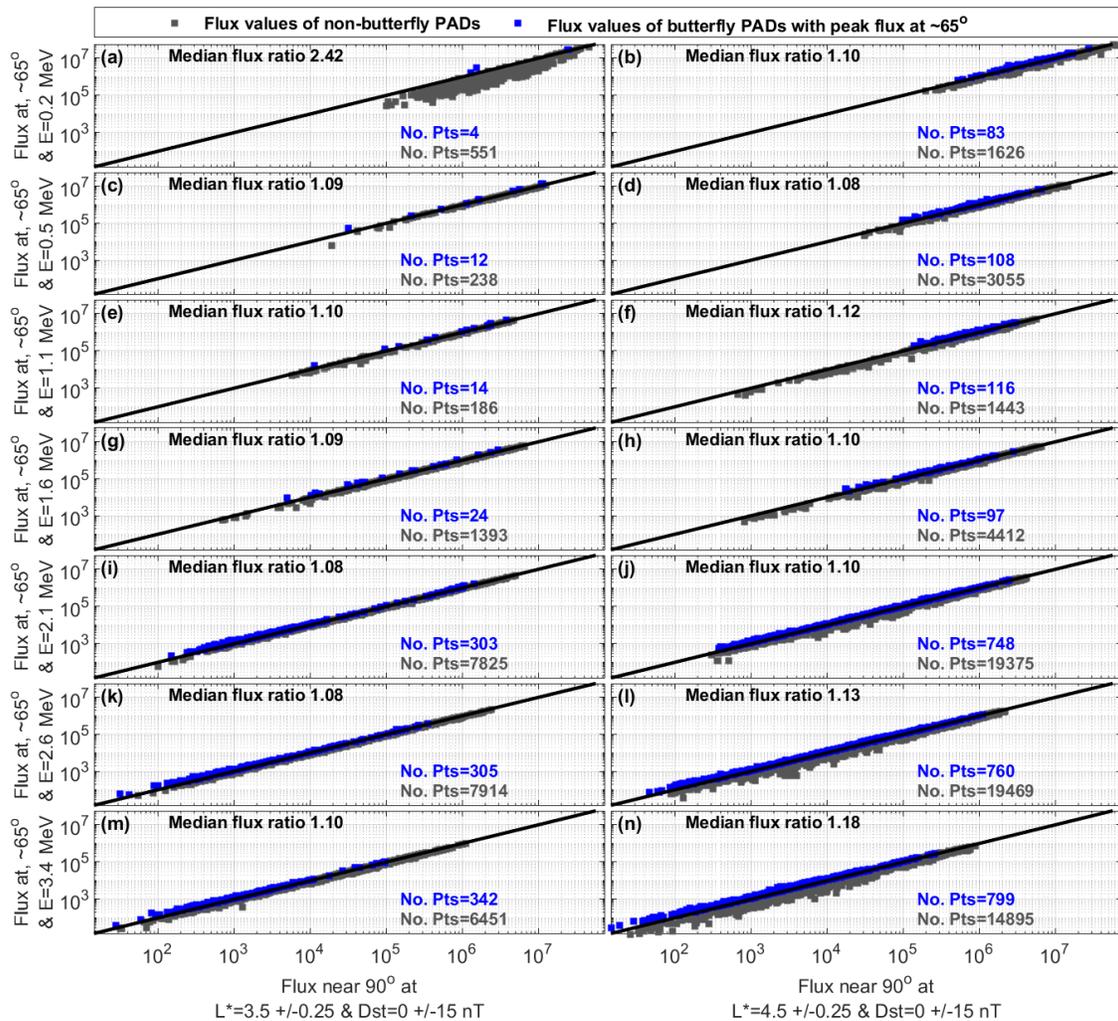
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Figure S21. The blue dots indicate results for butterfly PADs that have a peak flux at equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these non-butterfly PADs each data point represents the flux near an equatorial pitch angle of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° . Results shown here are for $Dst = -30 \pm 15$ nT at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in a similar format to the results presented in Figure 8 in the main paper.

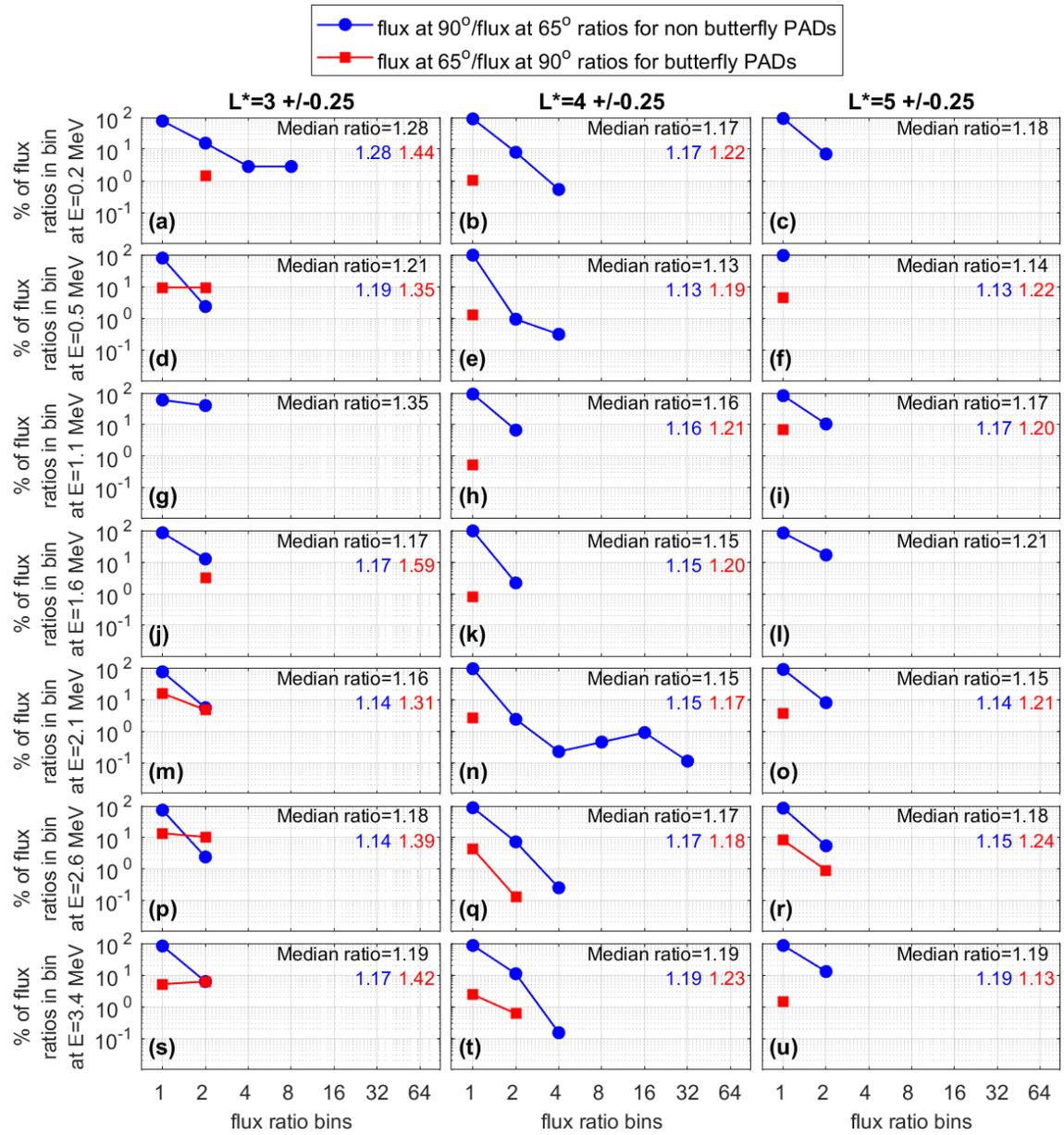


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288 **Figure S22.** The blue dots indicate results for butterfly PADs that have a peak flux at
 289 equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point
 290 represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak
 291 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 292 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 293 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 294 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° .
 295 Results shown here are for $Dst=0 \pm 15$ nT, in a similar format to the results
 296 presented in Figure 8 in the main paper.

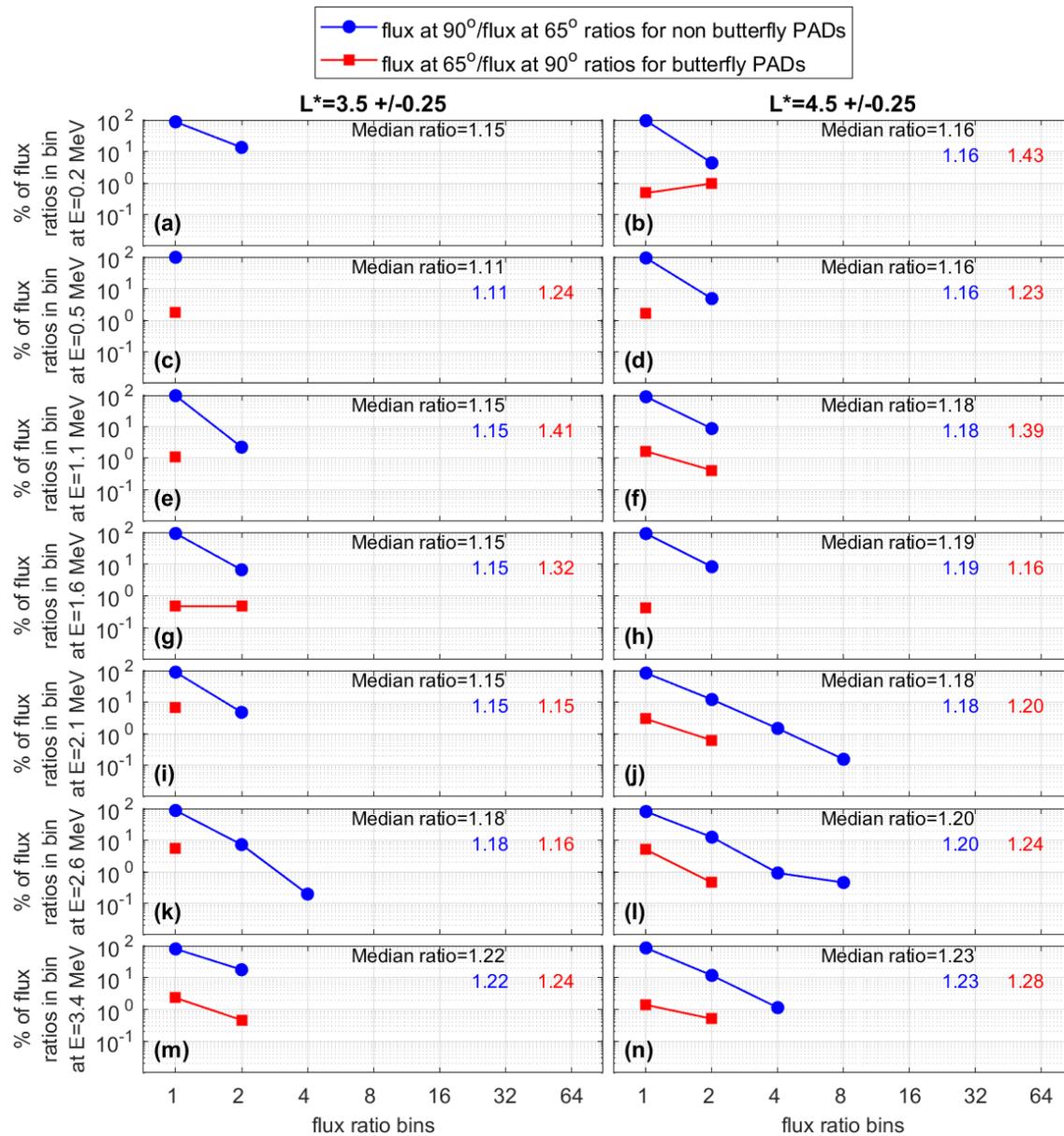
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300 **Figure S23.** The blue dots indicate results for butterfly PADs that have a peak flux at
 301 equatorial pitch angles of $65^\circ \pm 5^\circ$. For these butterfly PADs each data point
 302 represents the flux near equatorial pitch angles of 65° , where the flux reaches a peak
 303 value, versus the flux near equatorial pitch angles of 90° , where the flux is at a local
 304 minimum. Similarly, the gray dots indicate results for non-butterfly PADs. For these
 305 non-butterfly PADs each data point represents the flux near an equatorial pitch angle
 306 of 90° , where the flux peaks, versus the flux at an equatorial pitch angle of 65° .
 307 Results shown here are for $Dst=0 \pm 15$ nT at $L^*=3.5 \pm 0.25$ and $L^*=-4.5 \pm 0.25$ in a
 308 similar format to the results presented in Figure 8 in the main paper.
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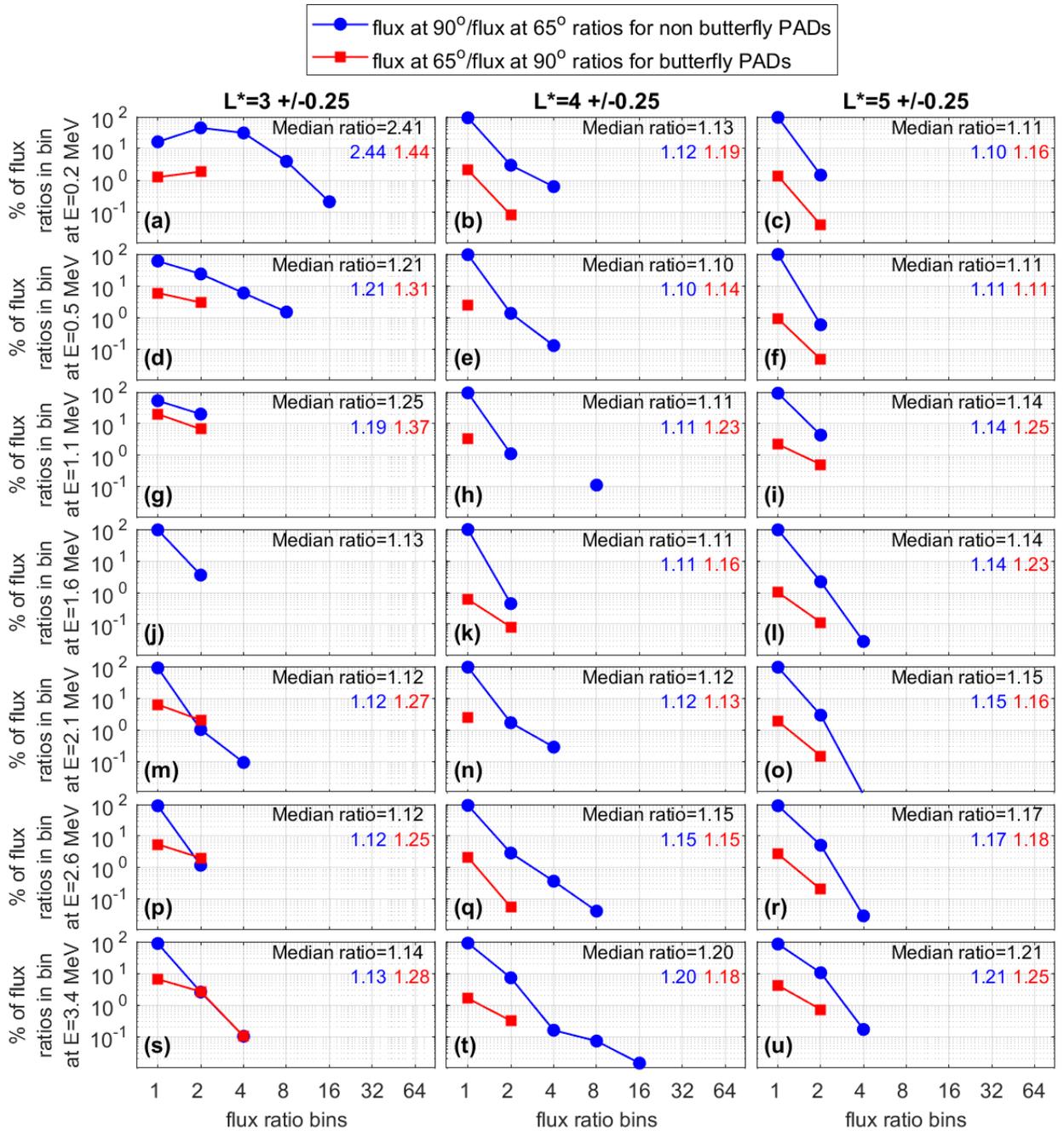
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Figure S24. The curves indicate how the flux values at equatorial pitch angles of $\sim 65^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -60 \text{ nT} \pm 15 \text{ nT}$, in the same format as the results presented in Figure 9 in the main paper.



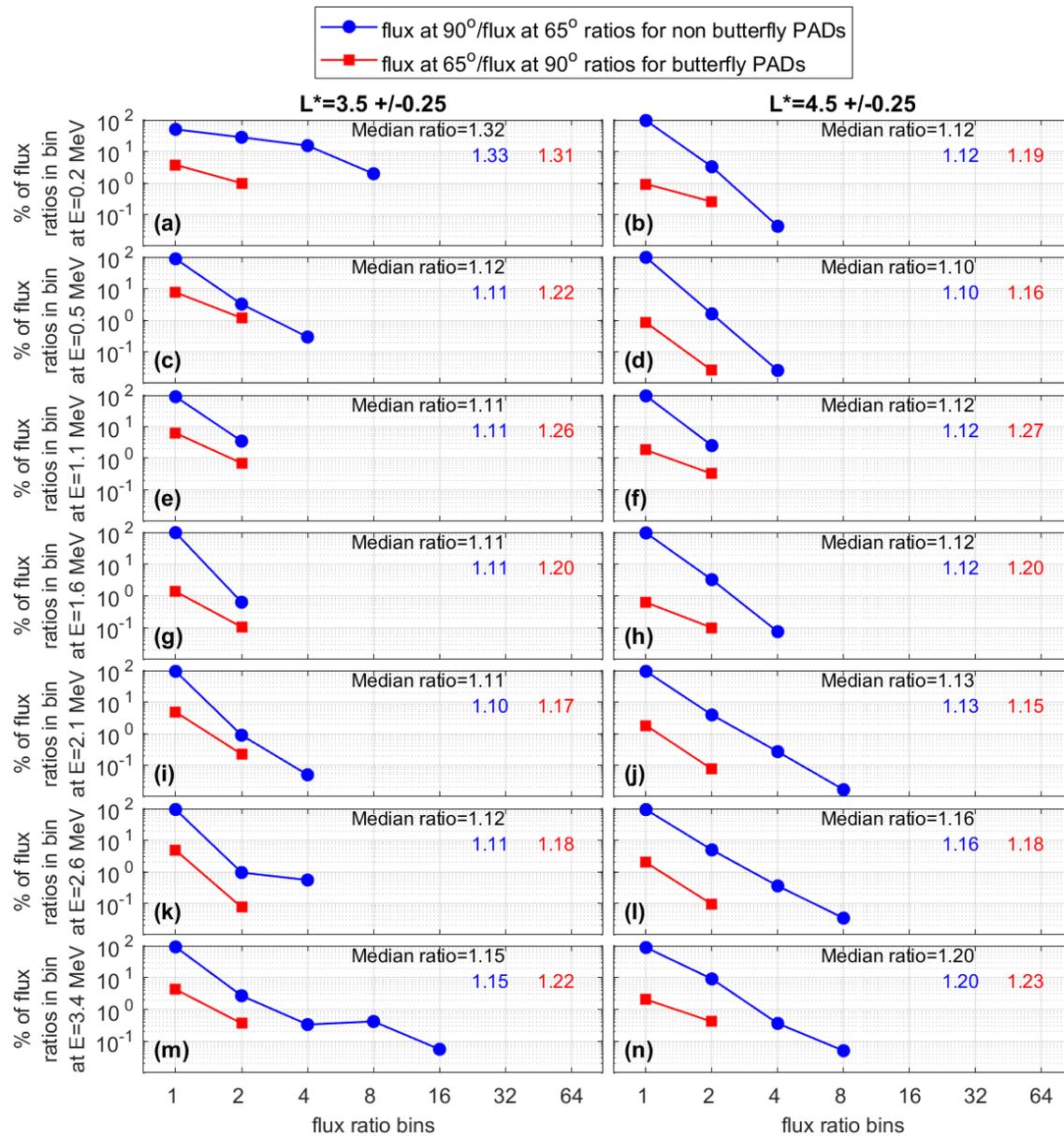
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Figure S25. The curves indicate how the flux values at equatorial pitch angles of $\sim 65^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -60 \text{ nT} \pm 15 \text{ nT}$ at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in the same format as the results presented in Figure 9 in the main paper.



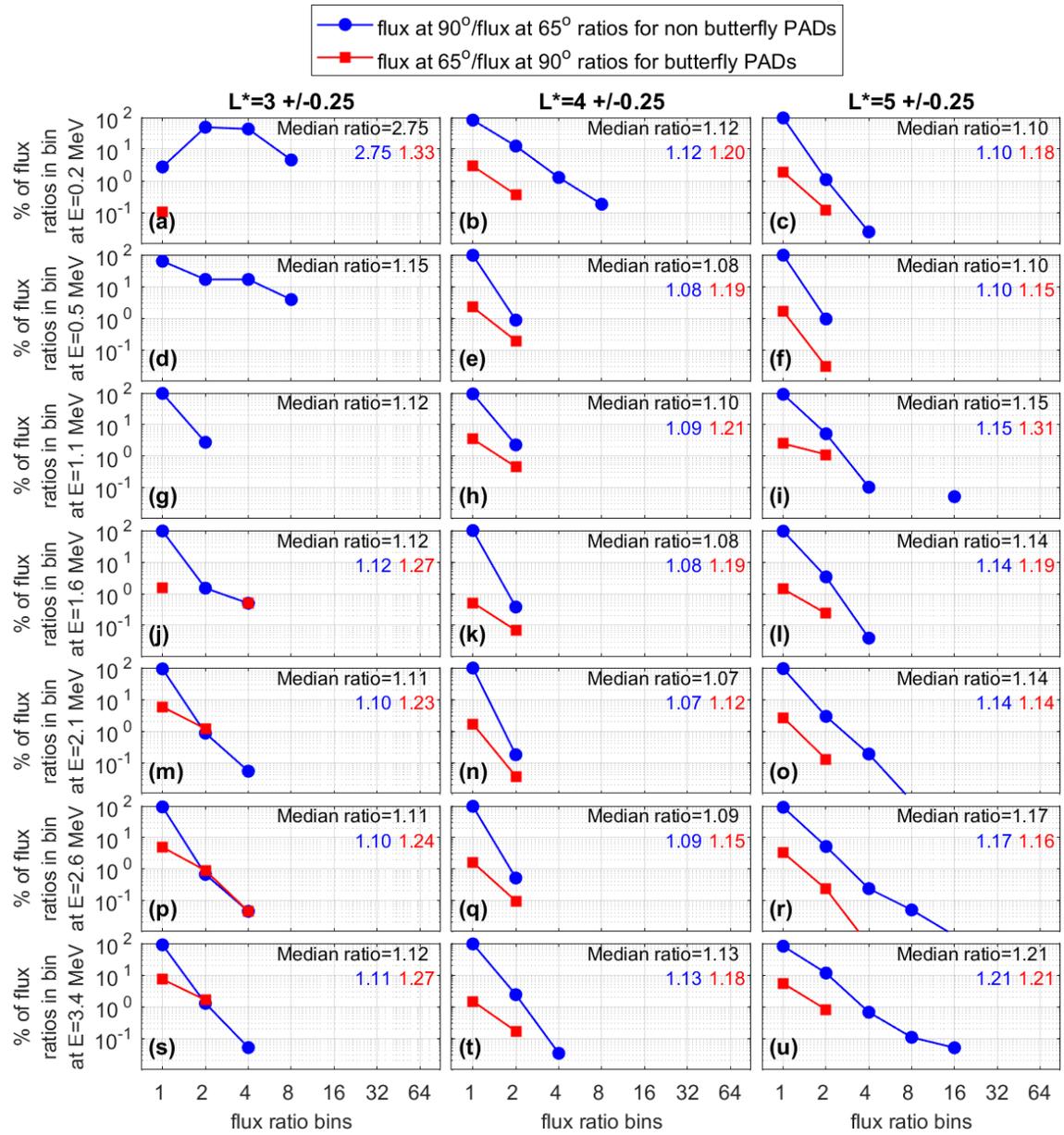
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Figure S26. The curves indicate how the flux values at equatorial pitch angles of $\sim 65^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -30 \text{ nT} \pm 15 \text{ nT}$, in the same format as the results presented in Figure 9 in the main paper.



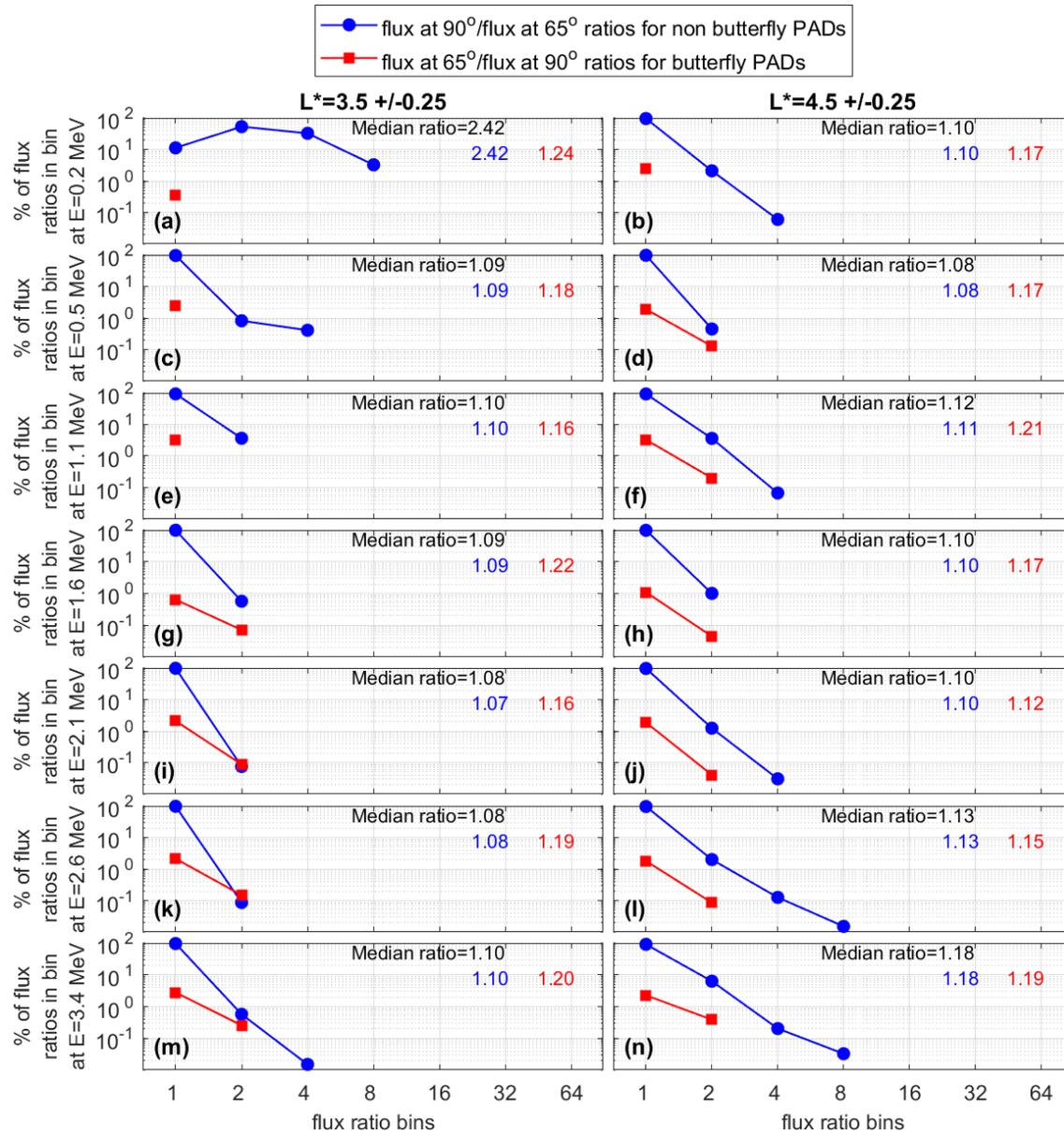
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Figure S27. The curves indicate how the flux values at equatorial pitch angles of $\sim 65^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst = -30 \text{ nT} \pm 15 \text{ nT}$ at $L^* = 3.5 \pm 0.25$ and $L^* = 4.5 \pm 0.25$ in the same format as the results presented in Figure 9 in the main paper.



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Figure S28. The curves indicate how the flux values at equatorial pitch angles of $\sim 65^\circ$ and $\sim 90^\circ$ differ. These results are for $Dst=0 \text{ nT} \pm 15 \text{ nT}$, in the same format as the results presented in Figure 9 in the main paper.



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Figure S29. The curves indicate how the flux values at equatorial pitch angles of ~65° and ~90° differ. These results are for Dst=0 nT ±15 nT at L*=3.5 ±0.25 and L*=4.5 ±0.25 in the same format as the results presented in Figure 9 in the main paper.