The Butterfly Effect?

Comparison of the morphology of high-energy Fermi-LAT events against sunspots

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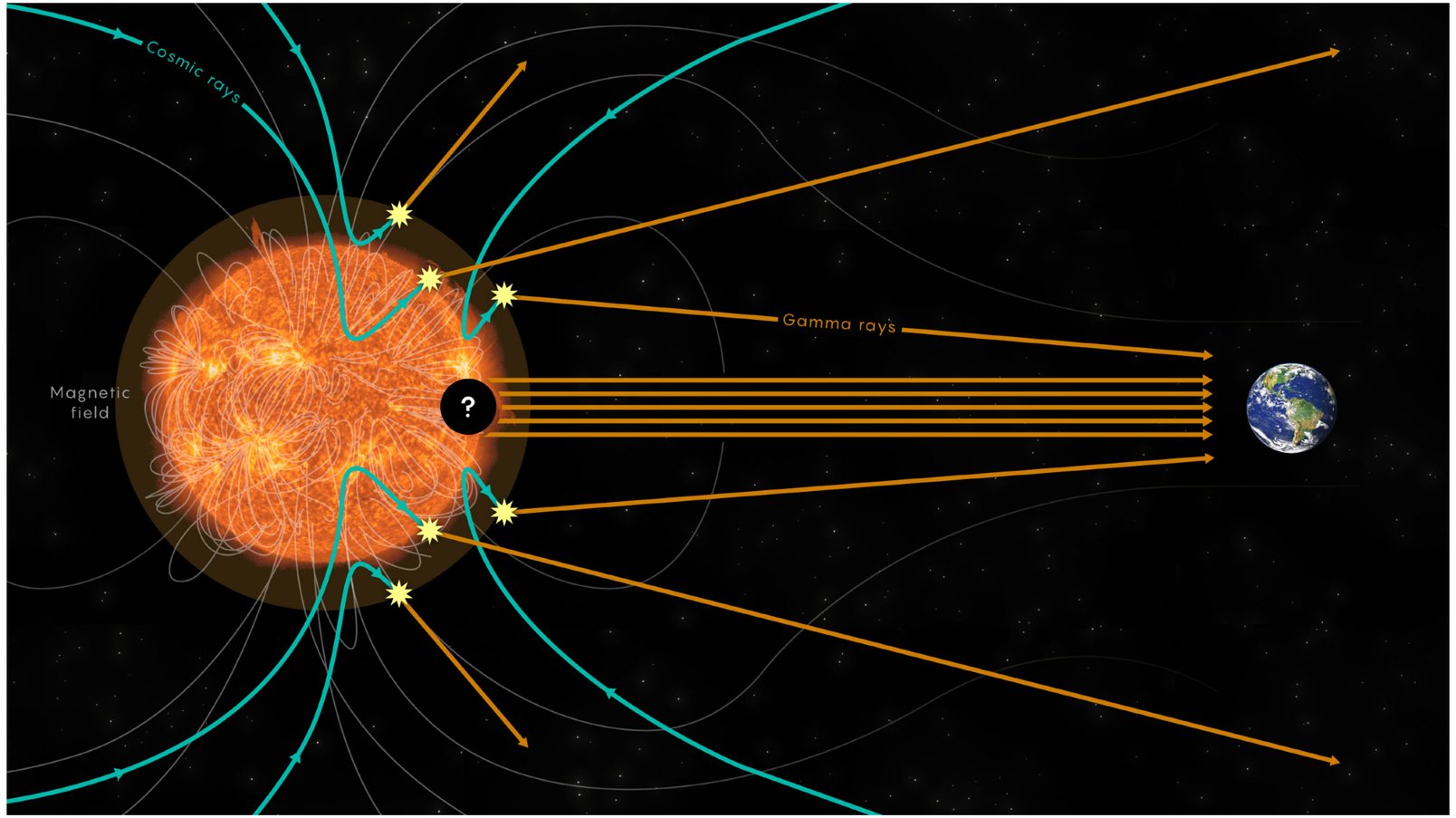
High Energy Solar Gamma Rays



Graphic from Quanta Magazine

- Origins of high energy solar gamma rays — cosmic rays hitting solar atmosphere
- Observed solar gamma flux is higher than predicted from Seckel et al. (1999)
- Linden et al. (2018) show variations of high energy solar gamma rays over the solar cycle
  - Is there a connection to sunspots as well?

High Energy Solar Gamma Rays
Linden et al. 2018

- Measured extremely high solar gamma ray flux
- Found strong time variation of solar gamma ray between solar minimum and the remaining solar cycle, especially for E > 50 GeV
  - Distinct polar and equatorial dependences

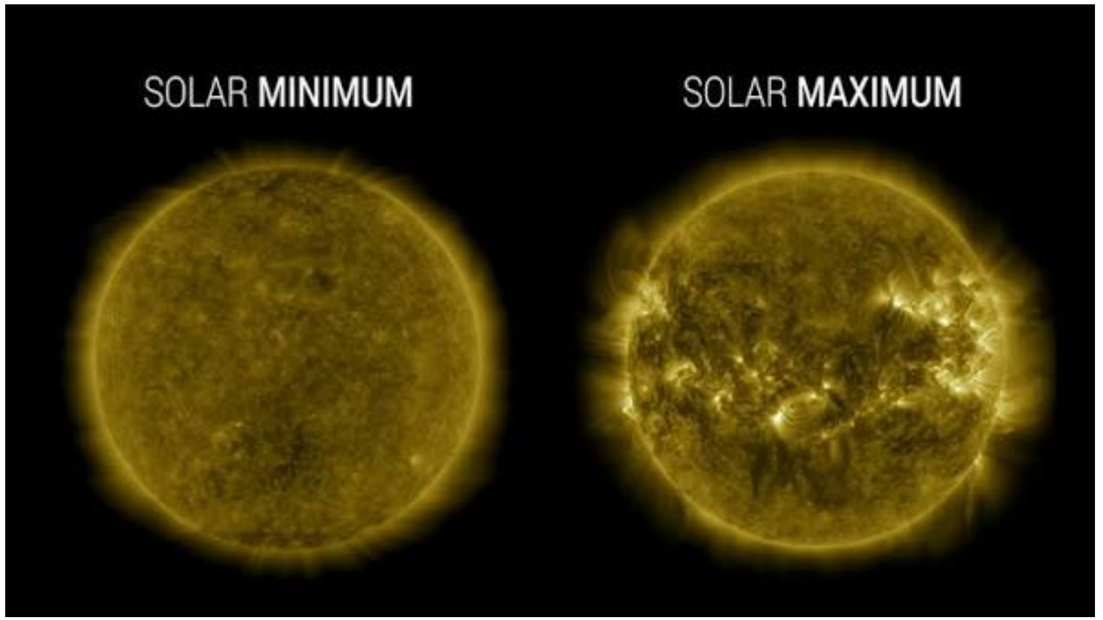


Image from NASA

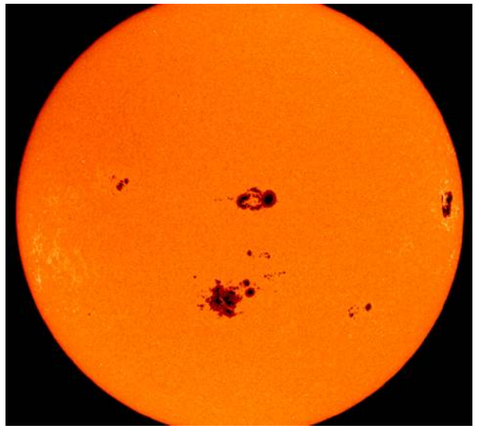
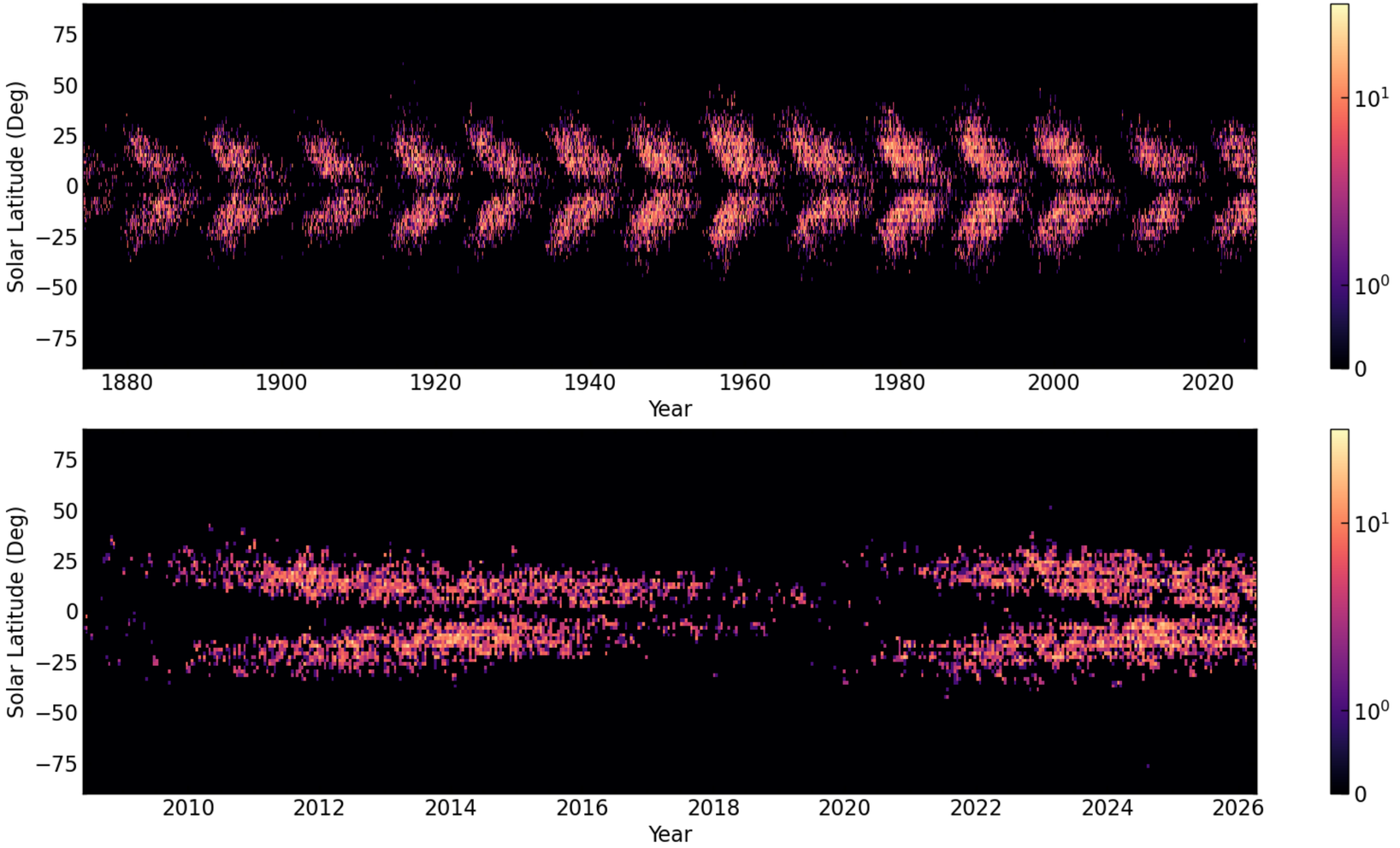


Image from NASA

Sunspots

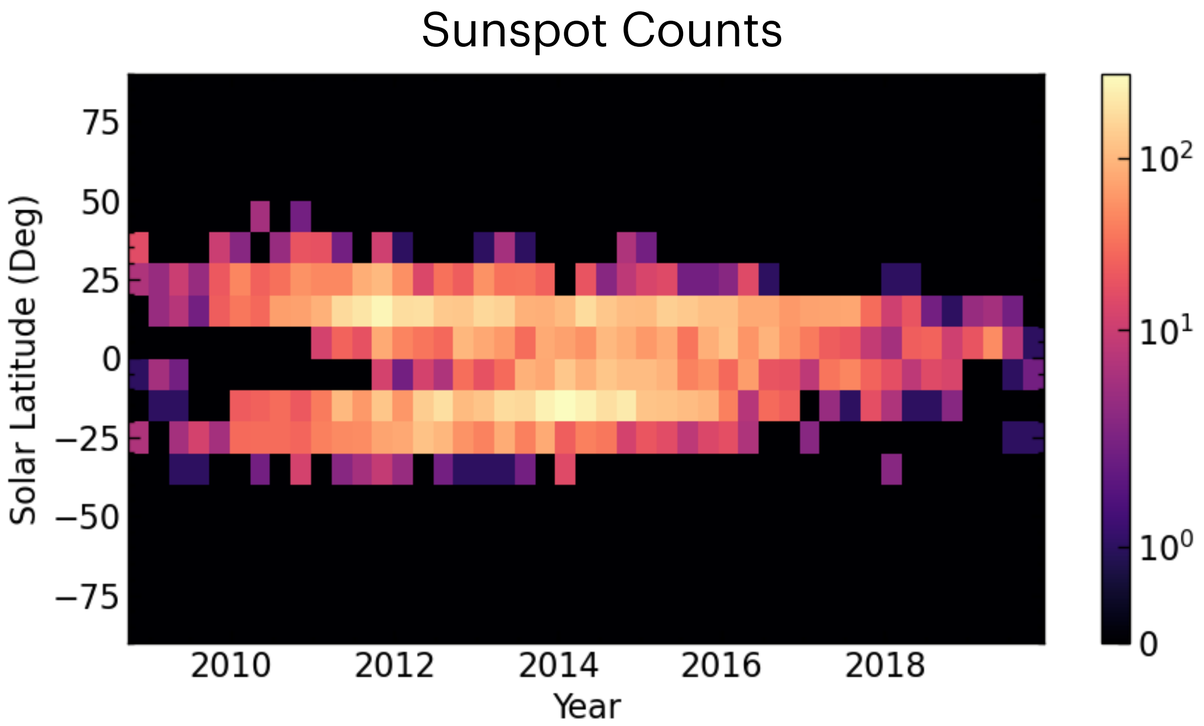
Butterfly Morphology

- Cooler, darker magnetic poles on solar surface
- Distinct butterfly-like shape of sunspots is a well known solar phenomenon
- We posit that high energy gamma rays move in the opposite direction (i.e. anti-correlated to sunspot morphology)



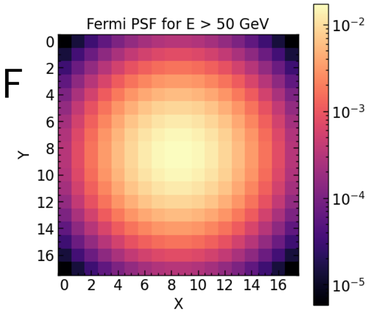
Sunspots

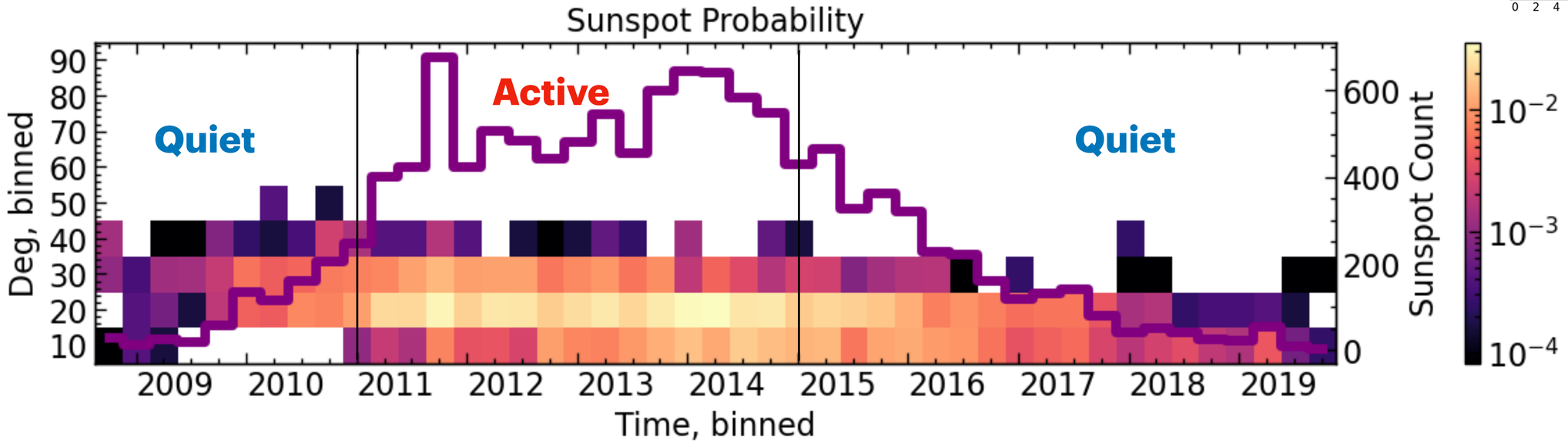
Sunspot Probability



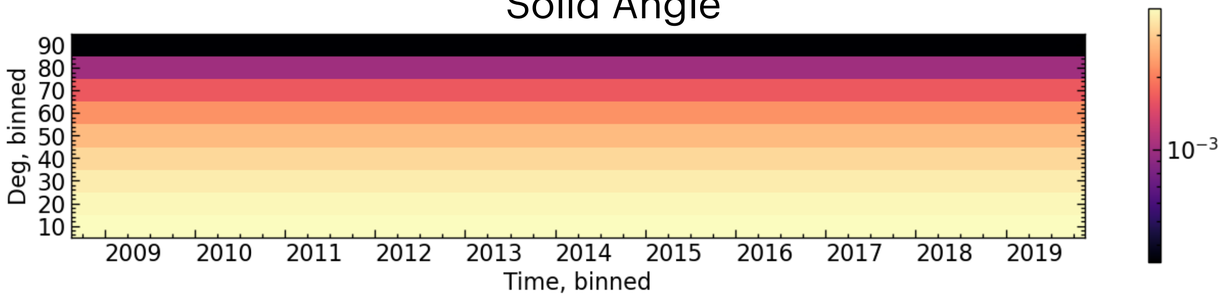
- Using solar sunspots over cycle 24 (2008-2019) and convert it to a probability density function (pdf)
  - In the x-axis, binned in three month periods
  - In the y-axis, binned in 10 degree bins
- Since this morphology from the sunspots are symmetrical, we take the absolute values of latitude degrees

Fermi PSF

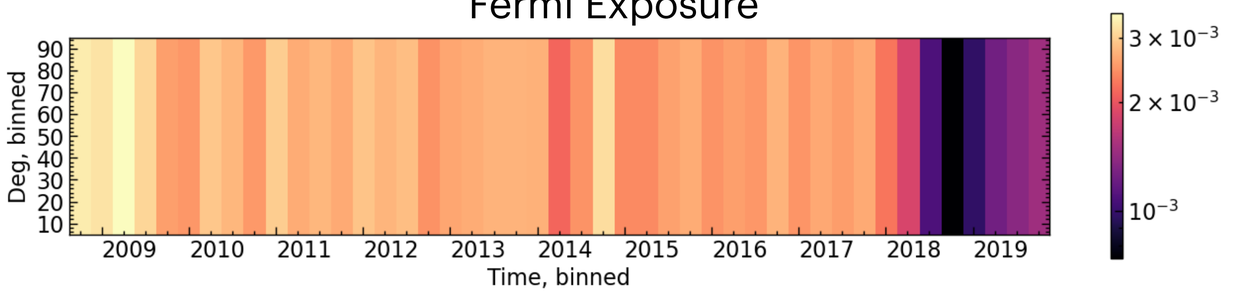




Solid Angle

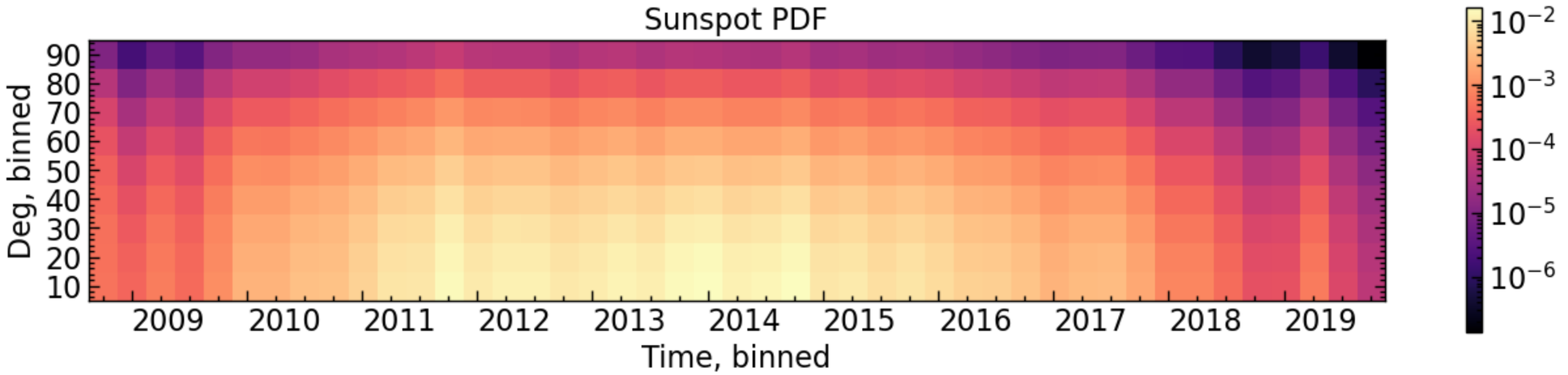


Fermi Exposure



Sunspots

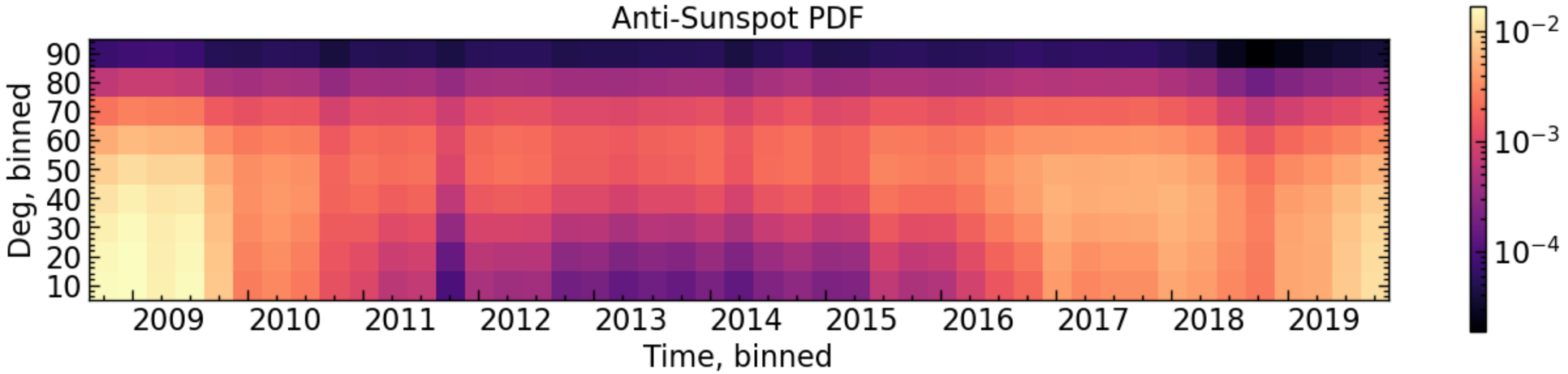
Sunspot PDF

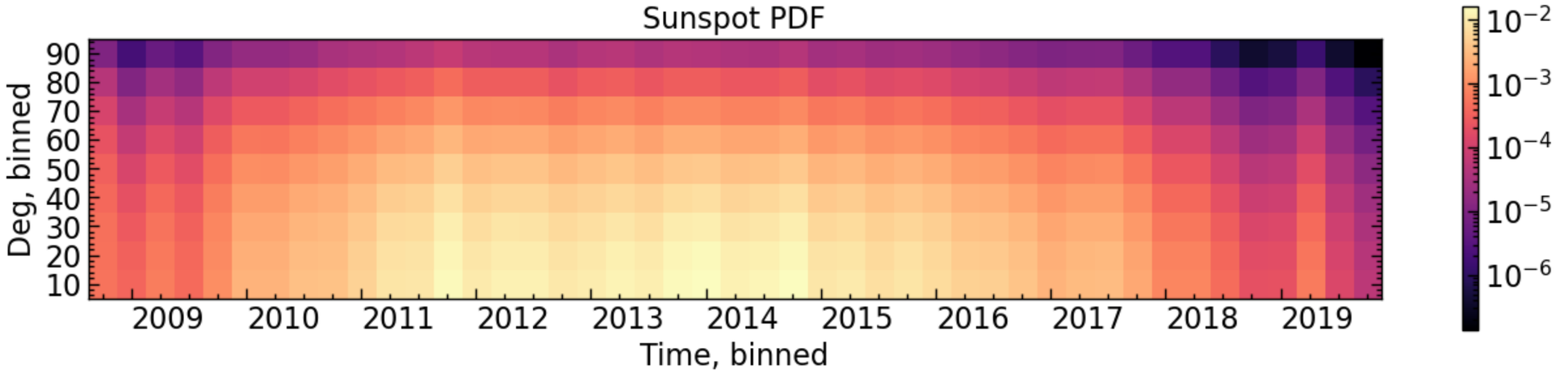


- Sunspot PDF generated incorporating normalised exposure time of Fermi, solid angle of sun, and Fermi's psf spread (E > 50 GeV)
  - Faster than applying onto gamma events directly
  - Sunspot features can still be seen

Sunspots
Anti-Sunspot PDF

- The anti-correlated sunspot PDF is generated by inverting sunspot probability
  - Fermi PSF, normalised Fermi exposure, and solar solid angle is applied back onto the inverted sunspot probability
- Rescaled for comparable range to sunspot pdf




Sunspot PDF
Deg, binned
90
80
70
60
50
40
30
20
10
2009
2010
2011
2012
2013
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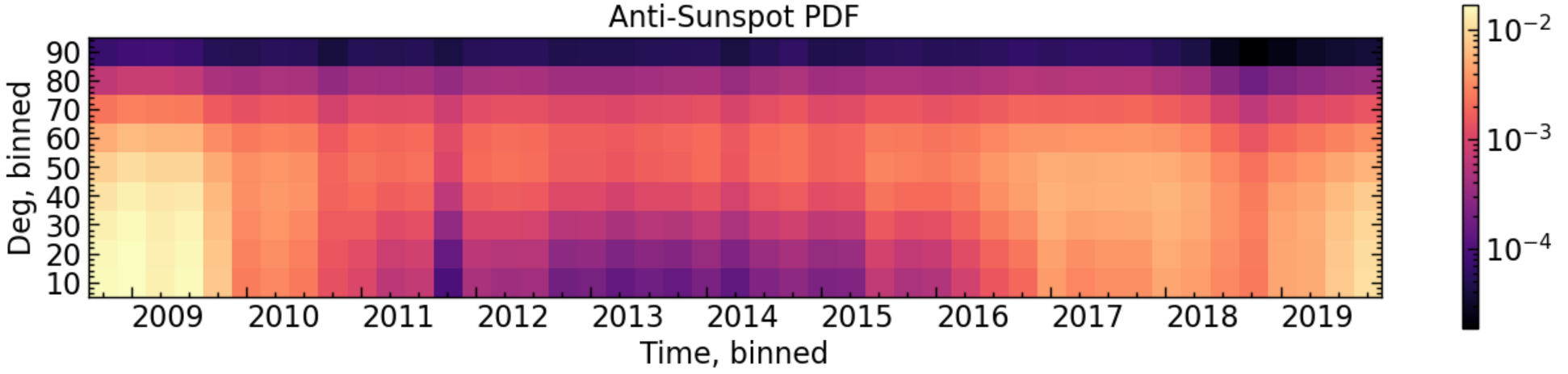
2016
2017
2018
2019
Time, binned
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}


Anti-Sunspot PDF
Deg, binned
90
80
70
60
50
40
30
20
10
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Time, binned
10^{-2}
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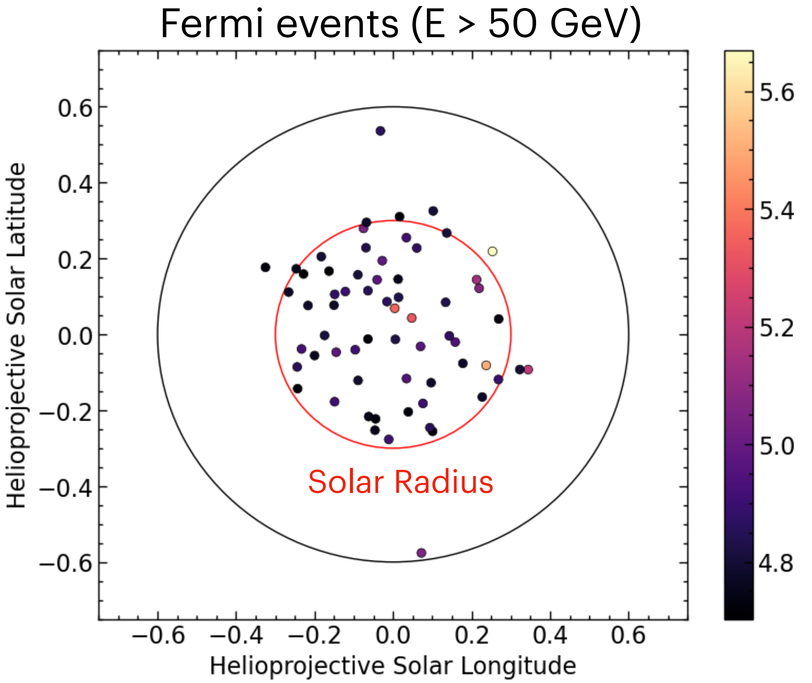
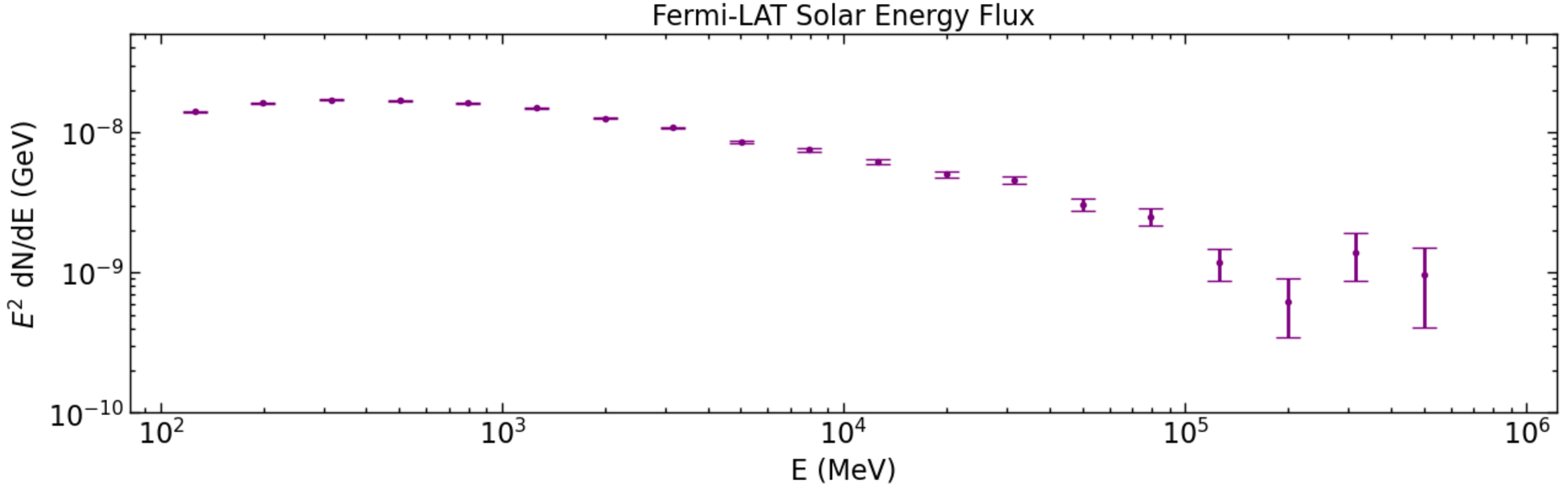
Fermi-LAT
Solar Flux

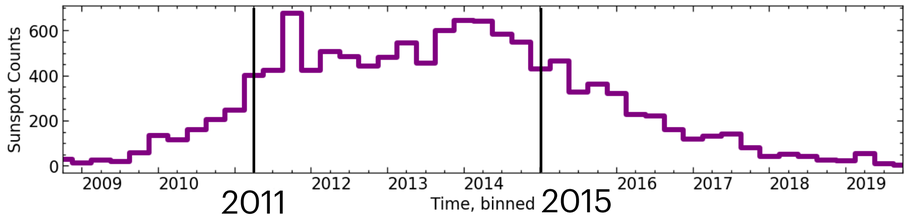
- Fermi-LAT data starts in 2008, covering the entire solar cycle from end of 2008-2019

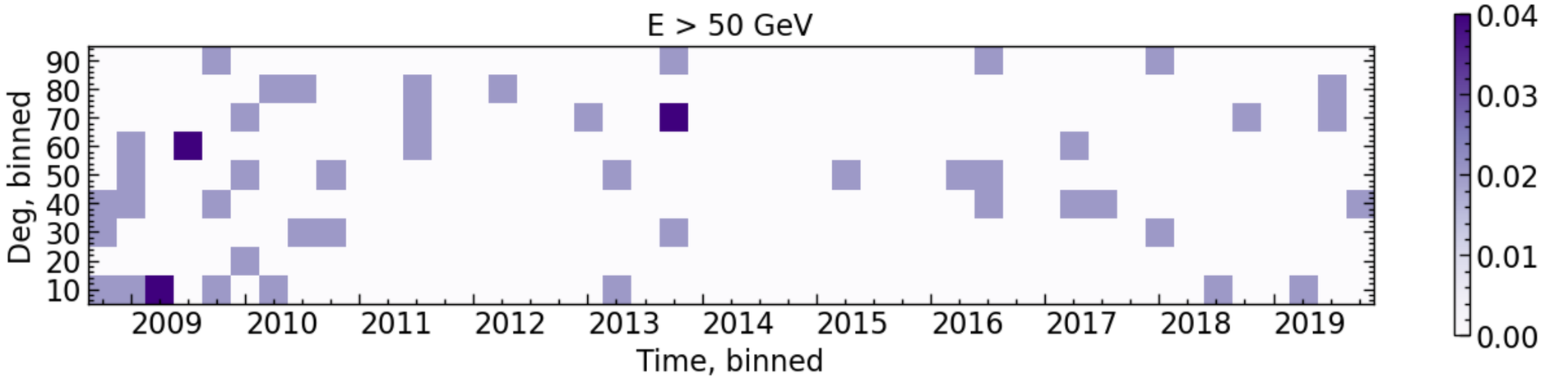


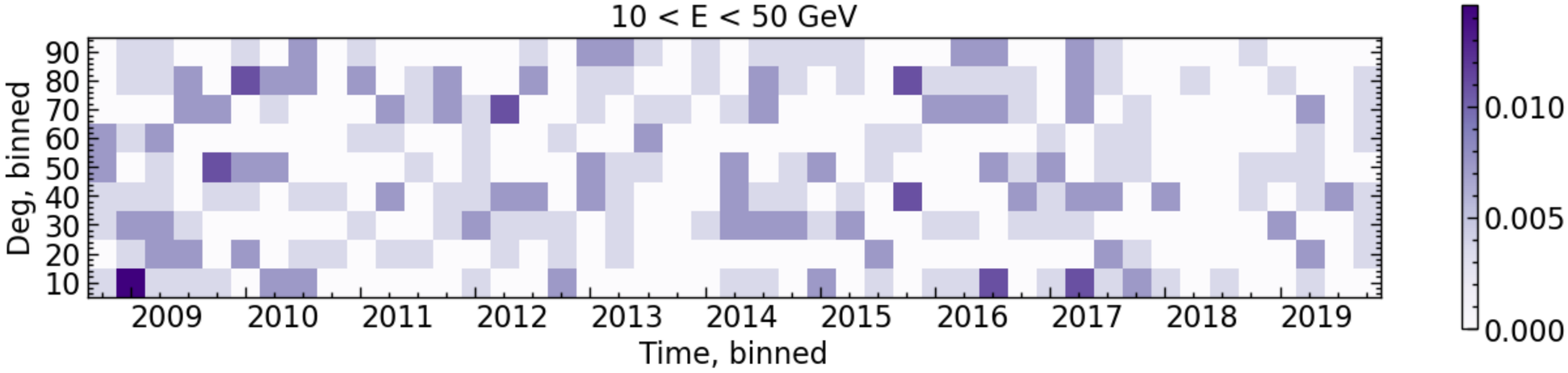


Fermi-LAT

Events probability map over solar cycle 24





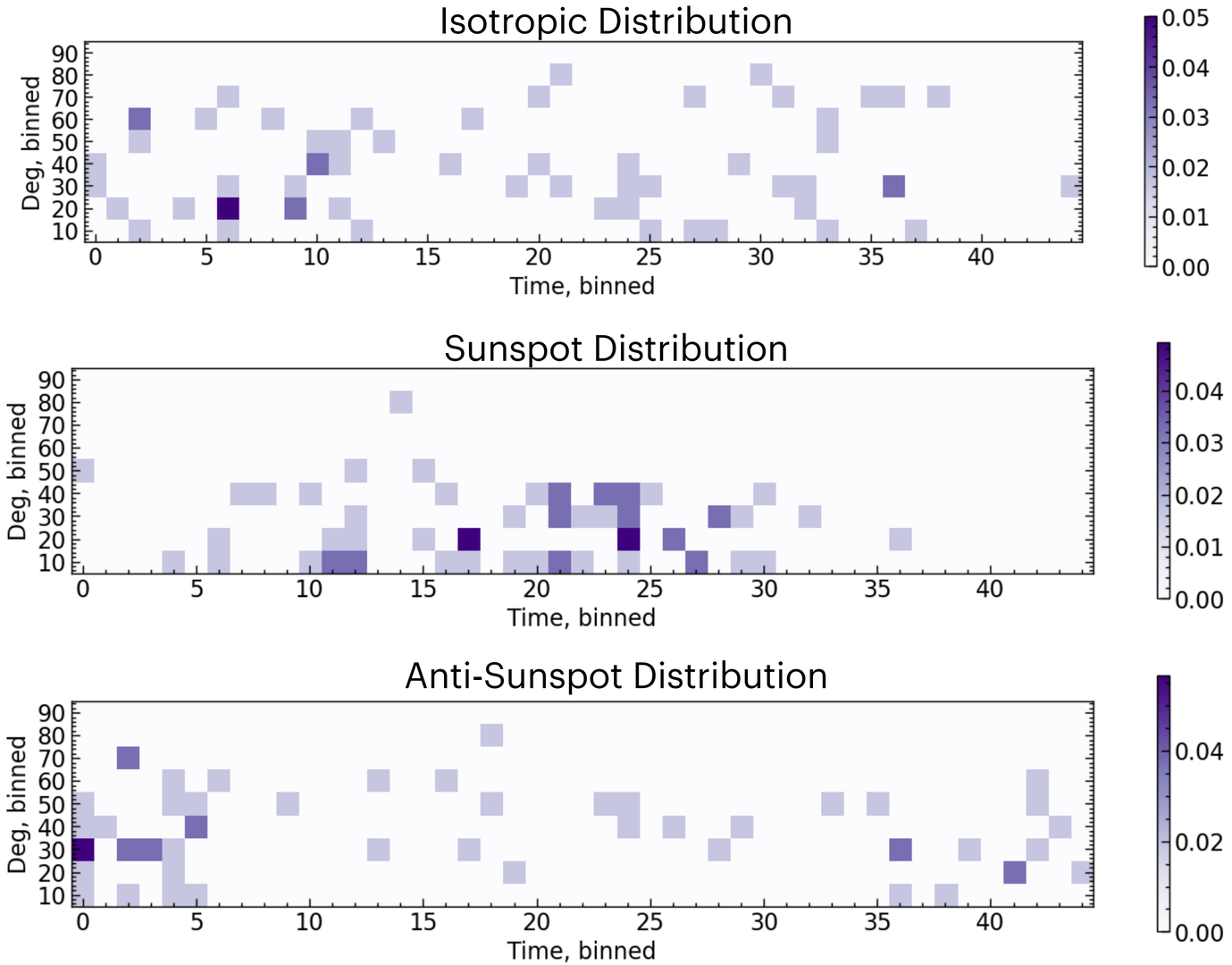


Statistical Tests
Analysis

- To compare the Fermi-LAT events against sunspots and its statistical dis/similarity to mock gamma events drawn from different sunspot distributions
    1. Generate isotropic, sunspot, and anti-correlated pdfs
    2. Events are drawn from these pdfs to create mock gamma distributions
    3. Calculate statistical similarity between mock distributions and pdfs
    4. Comparison of similarity of mock distributions and pdfs to Fermi gamma events and pdfs

Statistical Tests

- Three different mock gamma distribution events are shown, drawn from the isotropic, sunspot, and anti-sunspot pdf
- Different morphology of mock distributions is clear



Statistical Tests
Bhattacharyya Coefficient

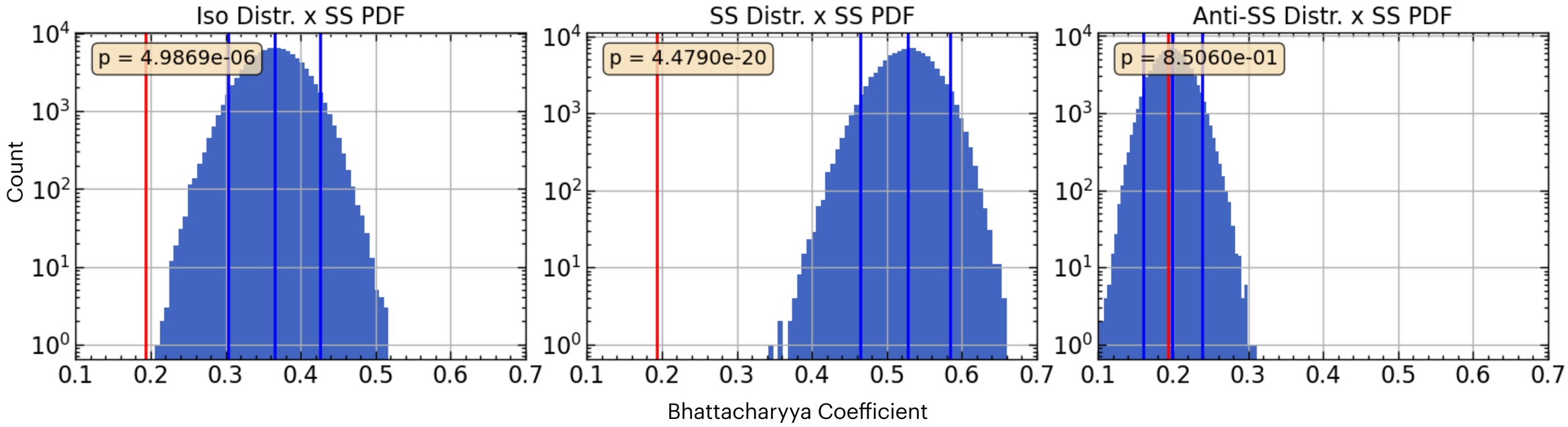
$$C_{Bhat} = \sum_{i=1}^{N} \sum_{j=1}^{M} \sqrt{P_{i,j}(\gamma) * P_{i,j}(ss)}$$

- Calculates overlap between each element of two probability distributions
- Ranges from (0, 1) between no overlap to identical distributions

Bhattacharyya Coefficient

- Focusing on the comparison between mock gamma events and the sunspot PDF
  - Statistically different to isotropic and sunspot like distributions — likely to be from anti-sunspot distribution

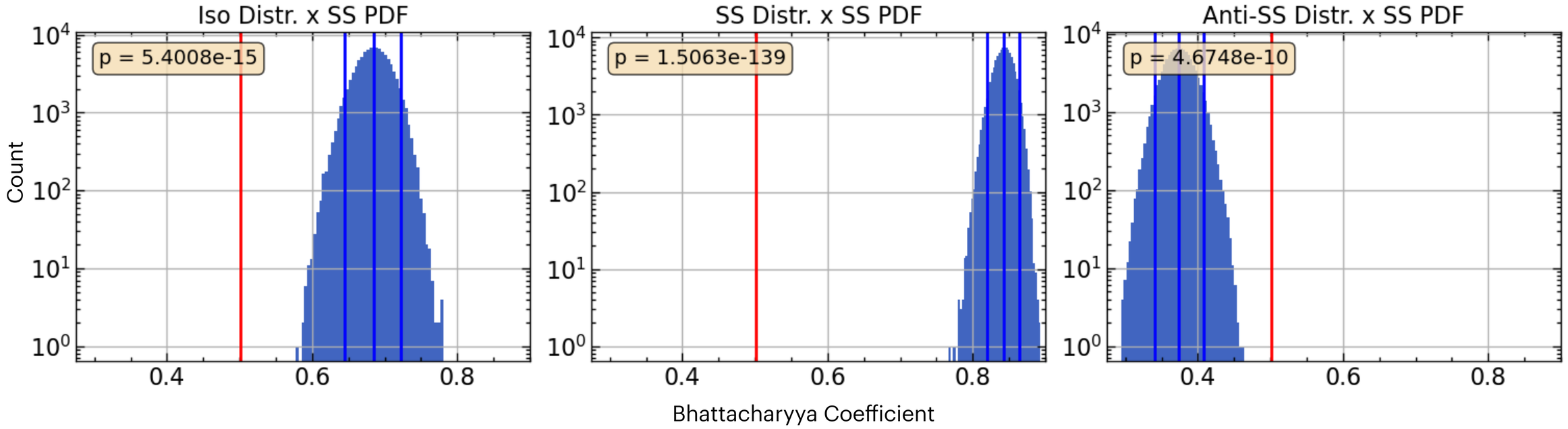
Comparisons to Fermi Gamma events **(E > 50 GeV)**



Discussion
Analysis

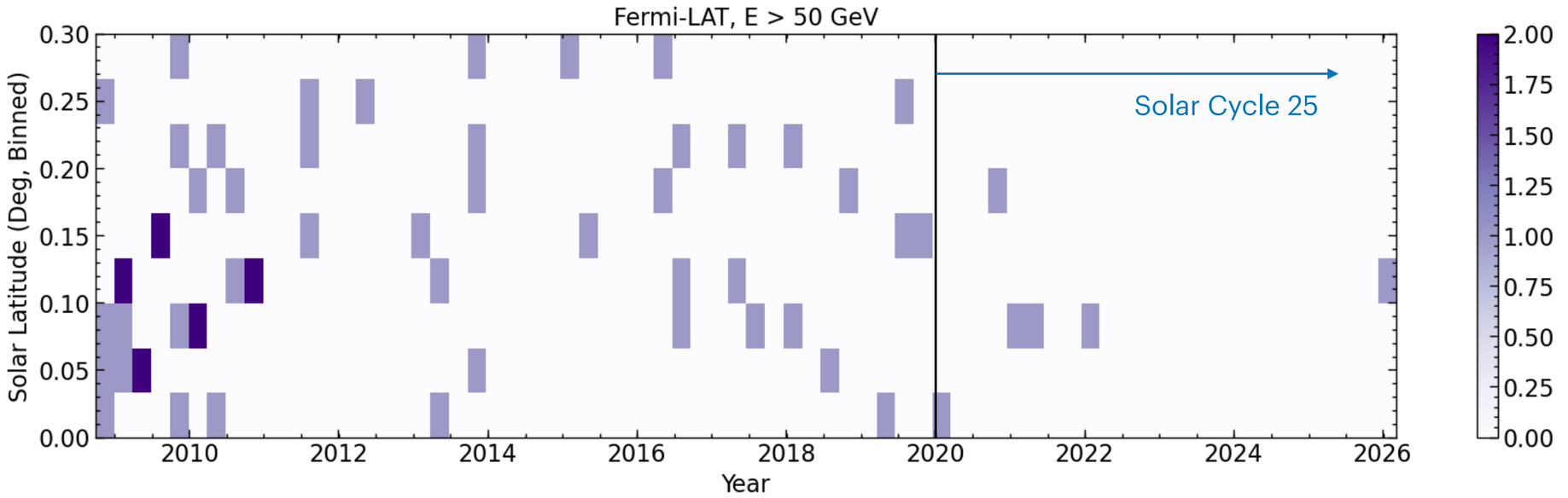
- The same pattern observed over three other statistical tests (Total Variation Distance, Hellinger Distance, JS Divergence)
  - Don’t see the same pattern with lower energy events

Comparisons to Fermi Gamma events **(10 < E < 50 GeV)**



Discussion
Statistics

- Low statistics from 2020 onwards (solar cycle 25) to compare
- Imperfect modeling of PDFs
- Not sure what mechanism may be responsible



Conclusions

1. Morphology of Fermi-LAT Gamma events of E > 50 GeV are quite unlikely to be similar to that of a sunspot-like distribution
   - Statistical tests indicate a distribution anti-correlated to sunspots seems preferable than an isotropic distribution
2. Need a longer timeframe to verify if anti-correlated pattern persists
3. Further work to determine mechanism that could cause anti-correlation

References and Acknowledgements

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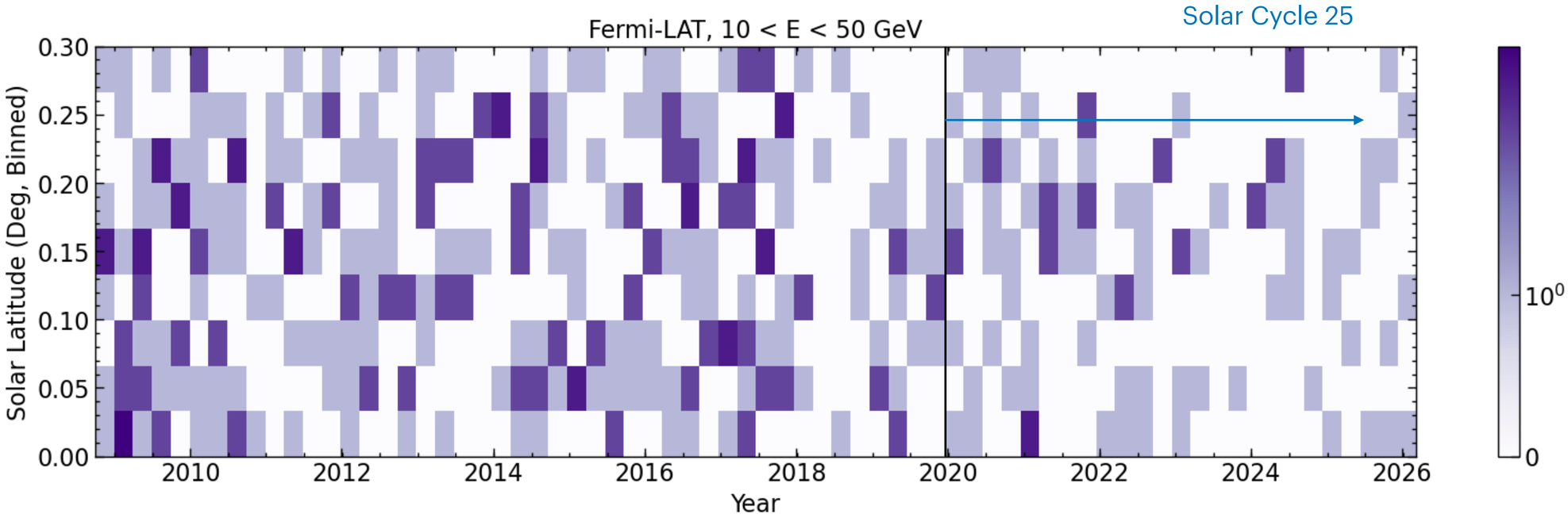
Thank you!

Extra Slides

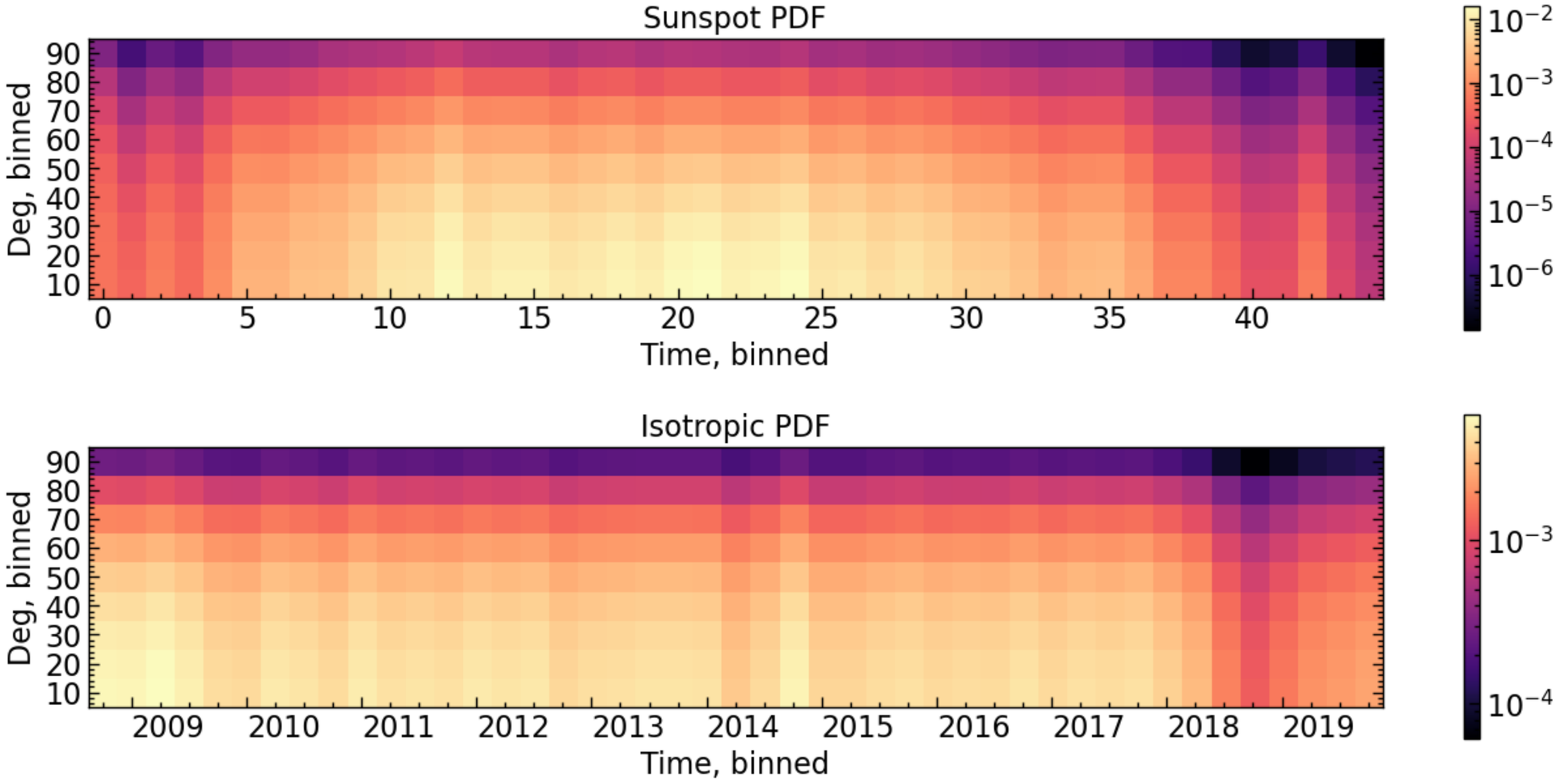
Fermi-LAT

Solar Gamma Events, 10 < E < 50 GeV, 2008-2026



Fermi-LAT

Sunspot PDF compared to Isotropic PDF

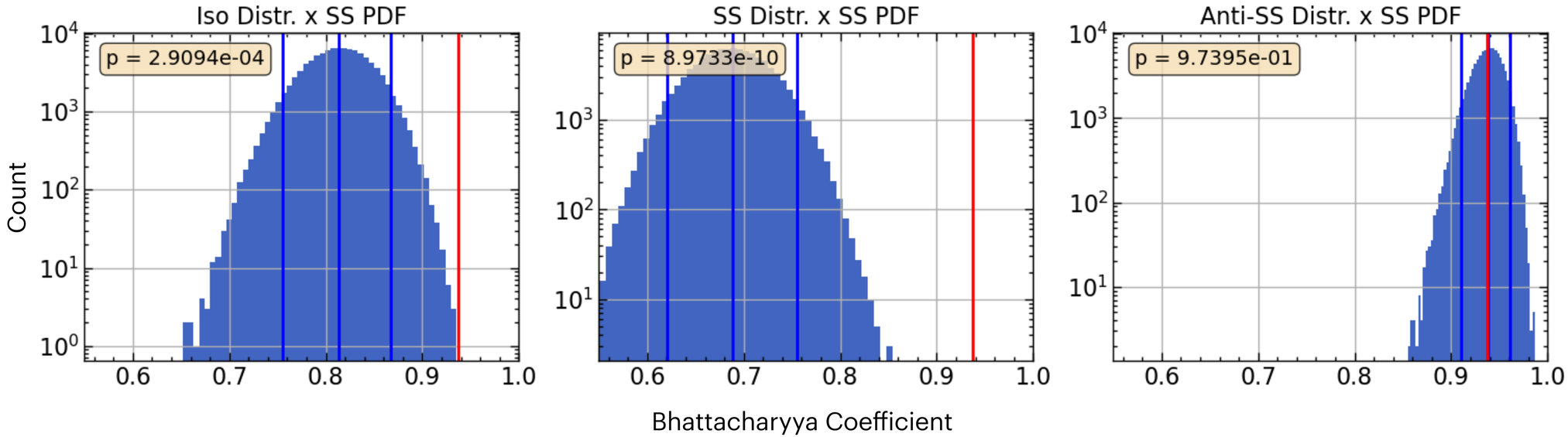


Statistical Tests

Total Variation Distance

$$TVD = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{M} P_{i,j}(\gamma) - P_{i,j}(ss)$$

- Calculates distance between corresponding elements of two distributions
- Ranges from (0, 1) from completely identical to no overlap

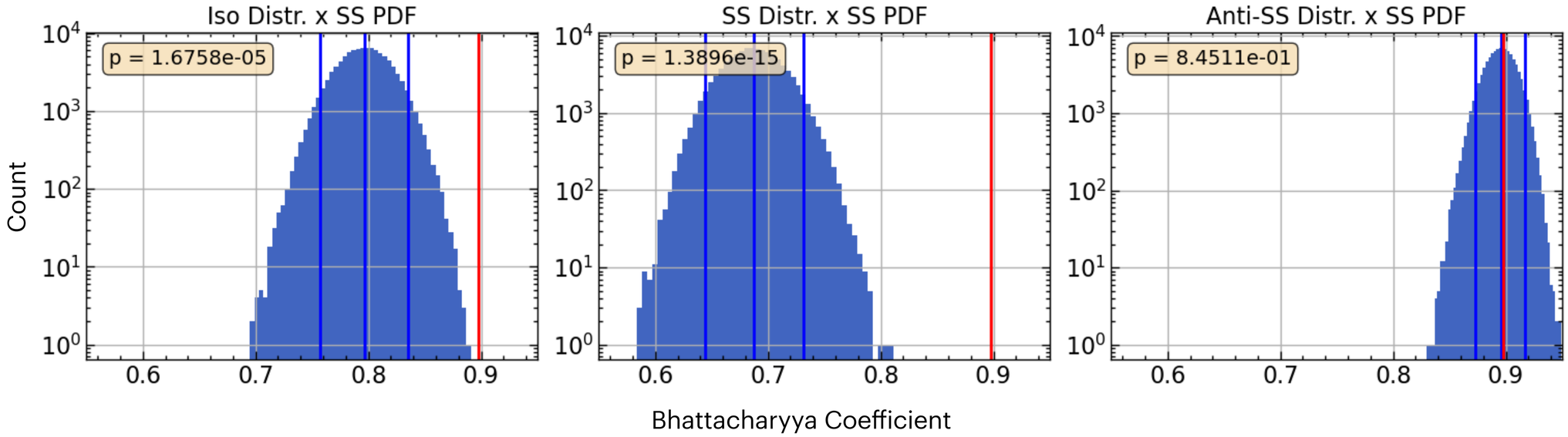


Statistical Tests

Hellinger Distance

$$D_{Hel} = \frac{1}{\sqrt{2}} \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{M} \left(\sqrt{P_{i,j}(\gamma)} - \sqrt{P_{i,j}(ss)} \right)^2}$$

- Measures dissimilarity between two probability distributions
- An extension of Bhattacharyya distance
- Ranges between (0, 1) from identical distributions to no overlap



Statistical Tests

Jensen-Shannon Divergence

$$M = \frac{1}{2}(P(ss) + P(\gamma))$$

$$JSD(P(\gamma) \quad P(ss)) = \frac{1}{2}D_{KL}(P(\gamma) \quad M) + \frac{1}{2}D_{KL}(P(ss) \quad M)$$

$$D_{KL}(P \quad Q) = \sum P_i log\frac{P_i}{Q_i}$$

- A measure of similarity between two distributions from their midpoint
- Derived from the Kullback-Leibler divergence
- Ranges between (0, 1) from identical distributions to no overlap