# One Model Doesn't Fit All: Recent Results of a Detailed Analysis of Sunspot Demographics

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www.solardynamo.org

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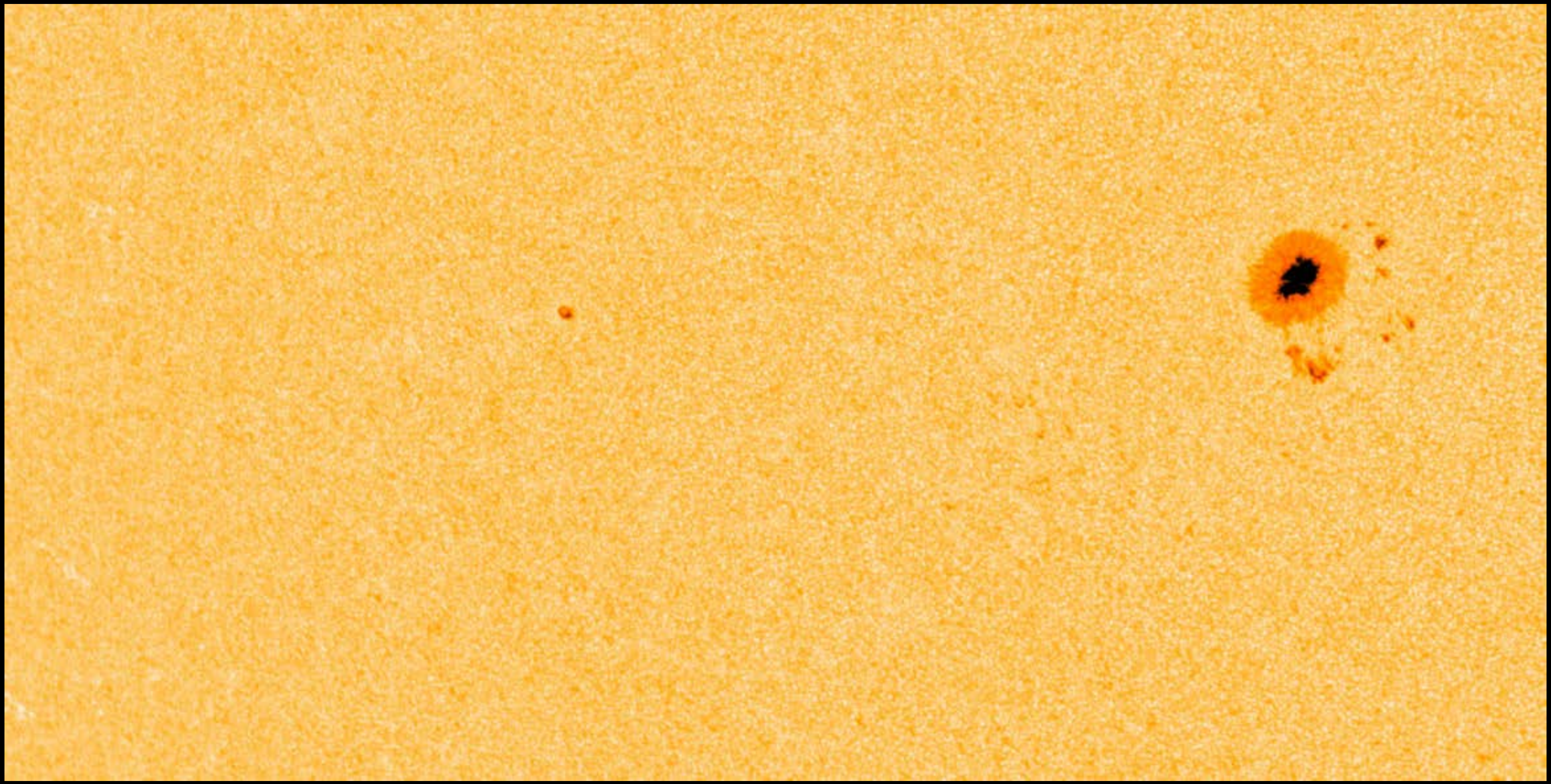
**Contract SP02H1701R from Lockheed-Martin to the SAO**
**NSF REU program**

# SUNSPOTS AND THE SOLAR CYCLE

# Sunspots are the optical signature of the presence of strong magnetic fields



SDO/HMI

They are generally associated with tilted bipolar magnetic regions.

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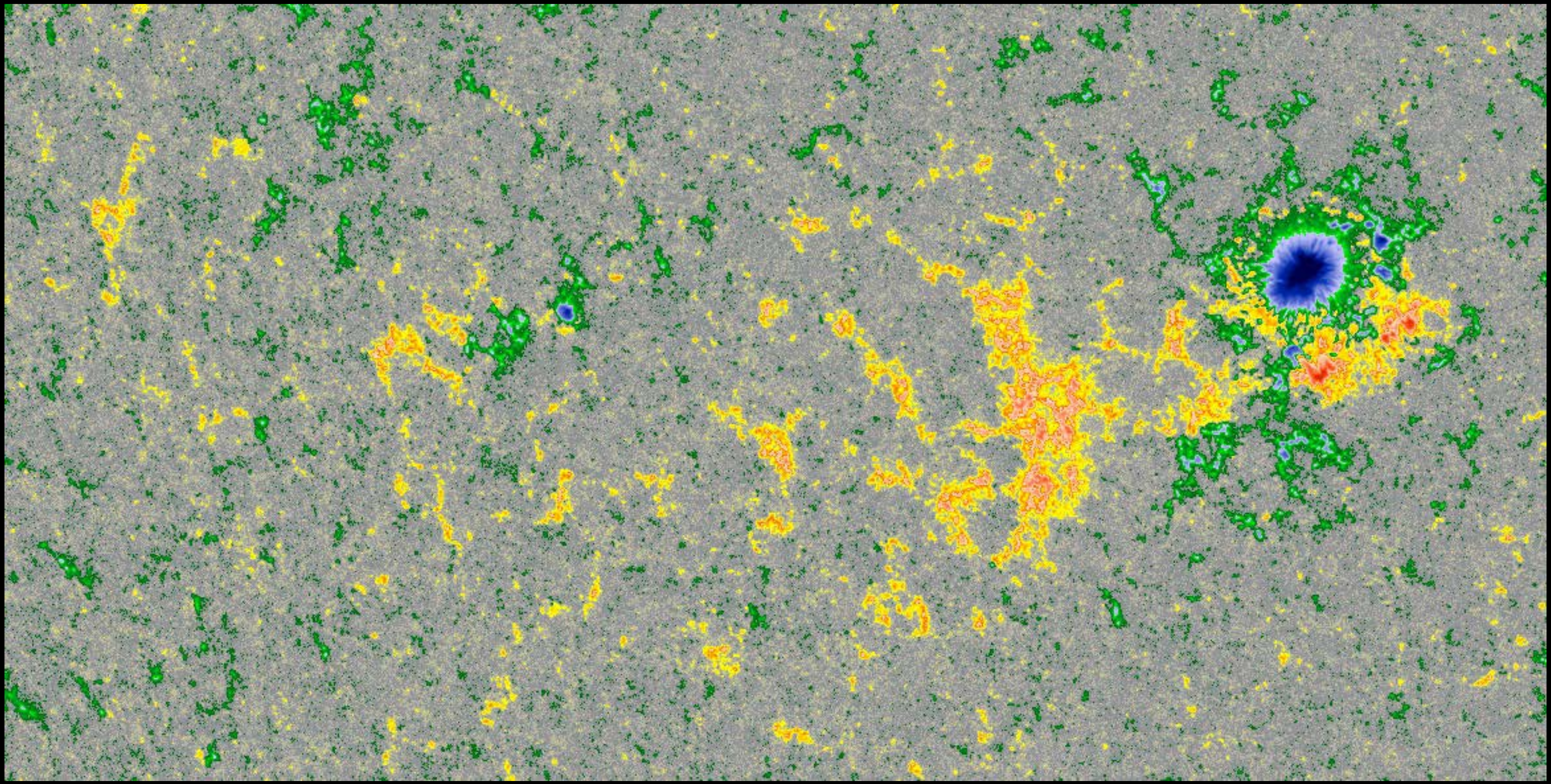

SDO/HMI

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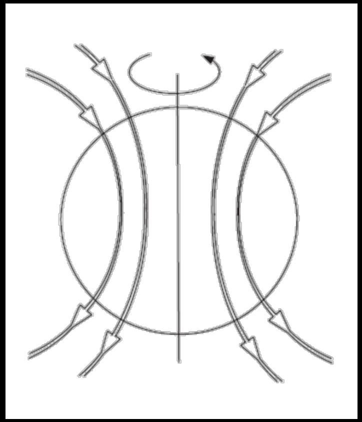
# BMRs are critical for cycle propagation

Muñoz-Jaramillo et al. ApJ (2012) & ApJL (2013)

Poloidal

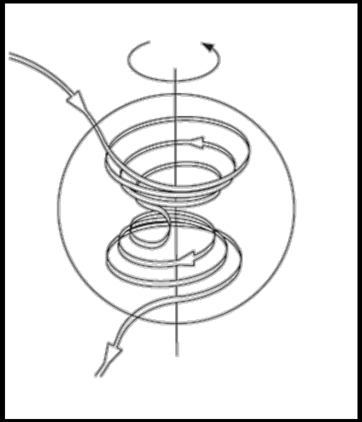
$r - \theta$



Polar Fields

Toroidal

$\phi$



Credit: J. J. Love

Sunspot Numbers/Area

# BMRs are critical for cycle propagation

Muñoz-Jaramillo et al. ApJ (2012) & ApJL (2013)

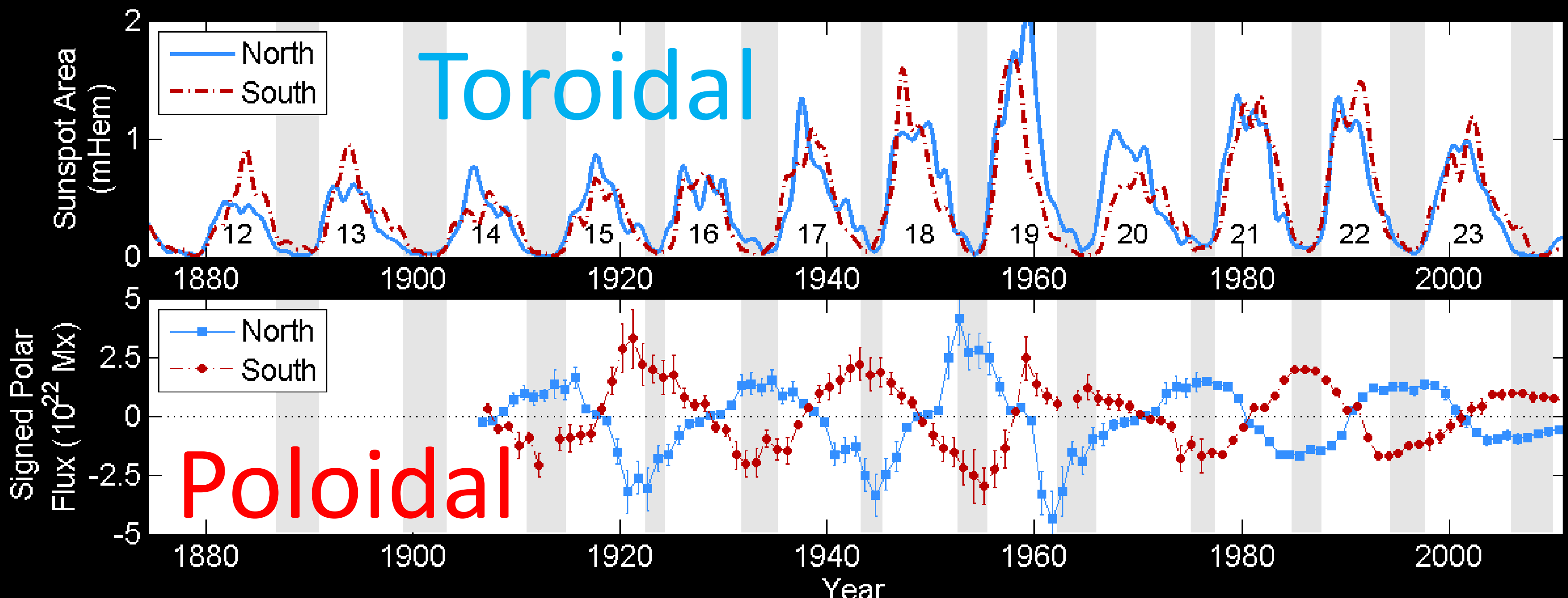
Poloidal

$r - \theta$

Toroidal

$\phi$

We used optical proxies to study the connection between toroidal and poloidal fields

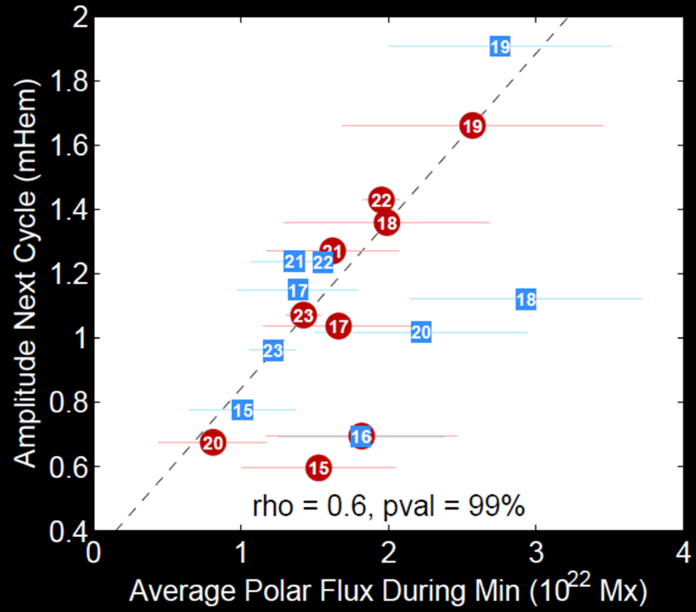


# BMRs are critical for cycle propagation

Muñoz-Jaramillo et al. ApJ (2012) & ApJL (2013)

Differential Rotation

**Poloidal** $r - \theta$ → **Toroidal** $\phi$




**The relationship between polar fields at minimum and cycle amplitude likes at the core of most physics based cycle predictions.**

# BMRs are critical for cycle propagation

Muñoz-Jaramillo et al. ApJ (2012) & ApJL (2013)

Poloidal

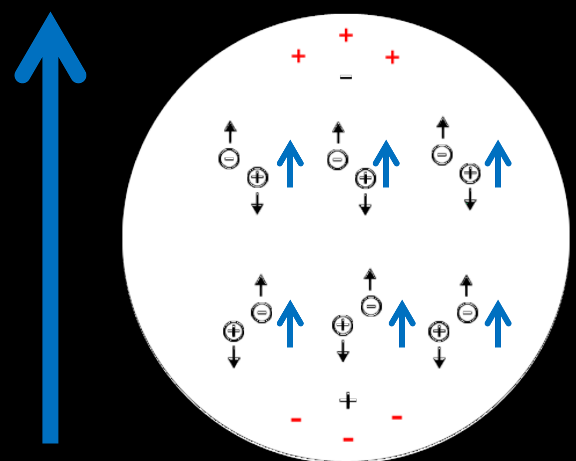
$r - \theta$

Differential Rotation

Toroidal

$\phi$

Emergence and Decay of Tilted Active Regions



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Muñoz-Jaramillo et al. ApJ (2012) & ApJL (2013)

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Differential Rotation →

← Emergence and Decay of Tilted Active Regions

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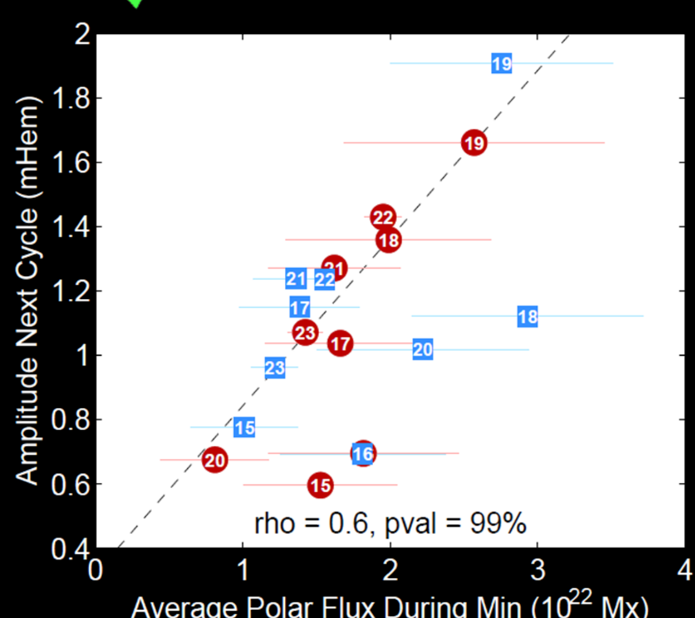


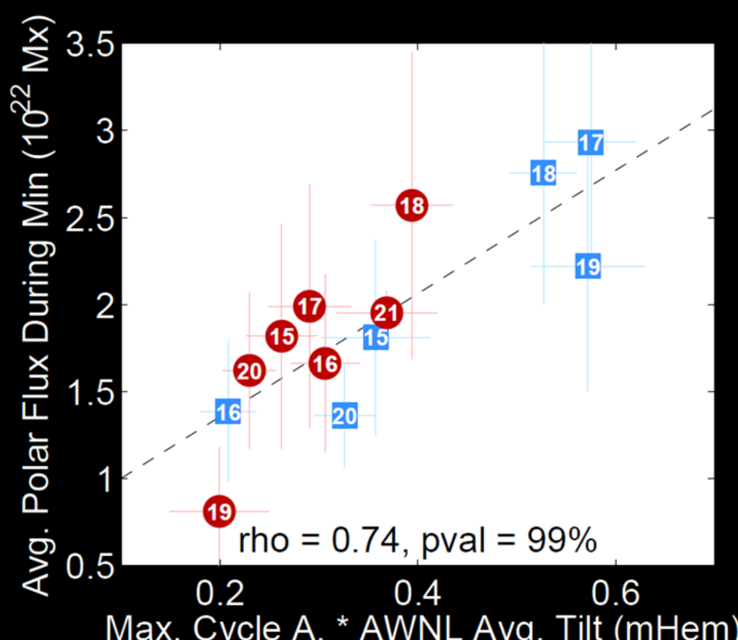

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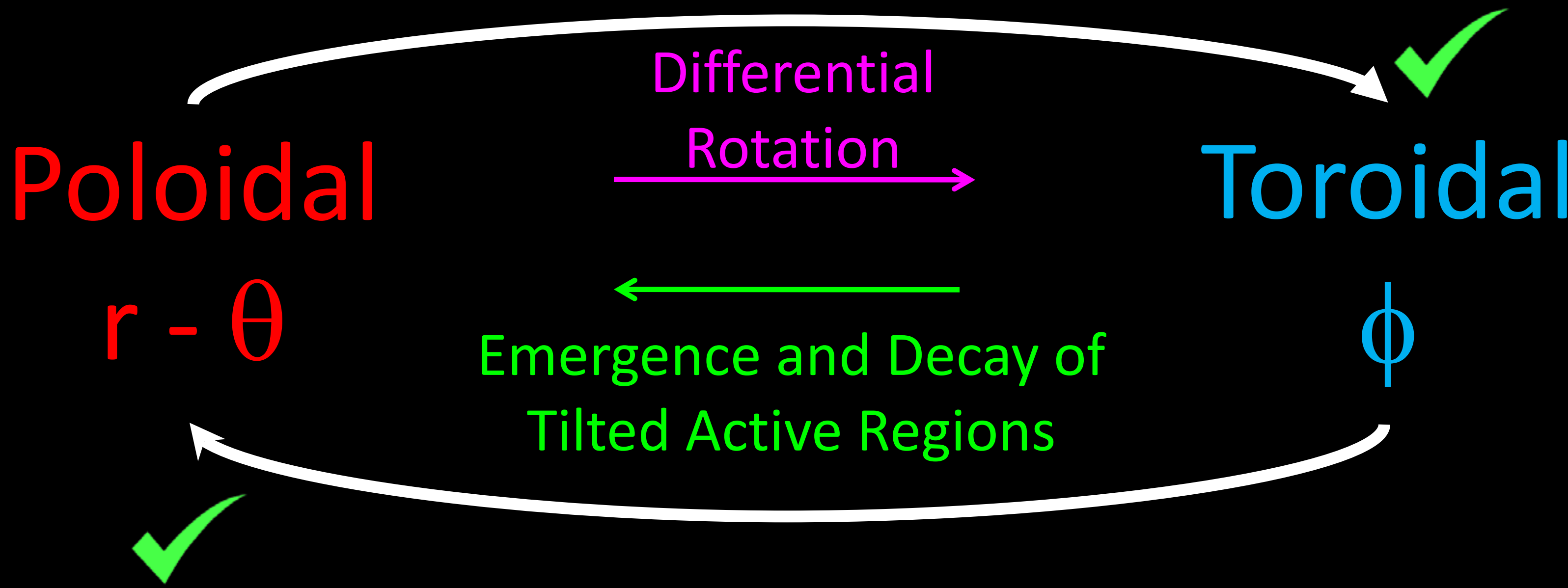



- **Our results are consistent with this picture of the solar cycle.**

- **BMR and sunspot properties are highly variable statistical characterizations are necessary.**

# OUR DATA

# Our Data

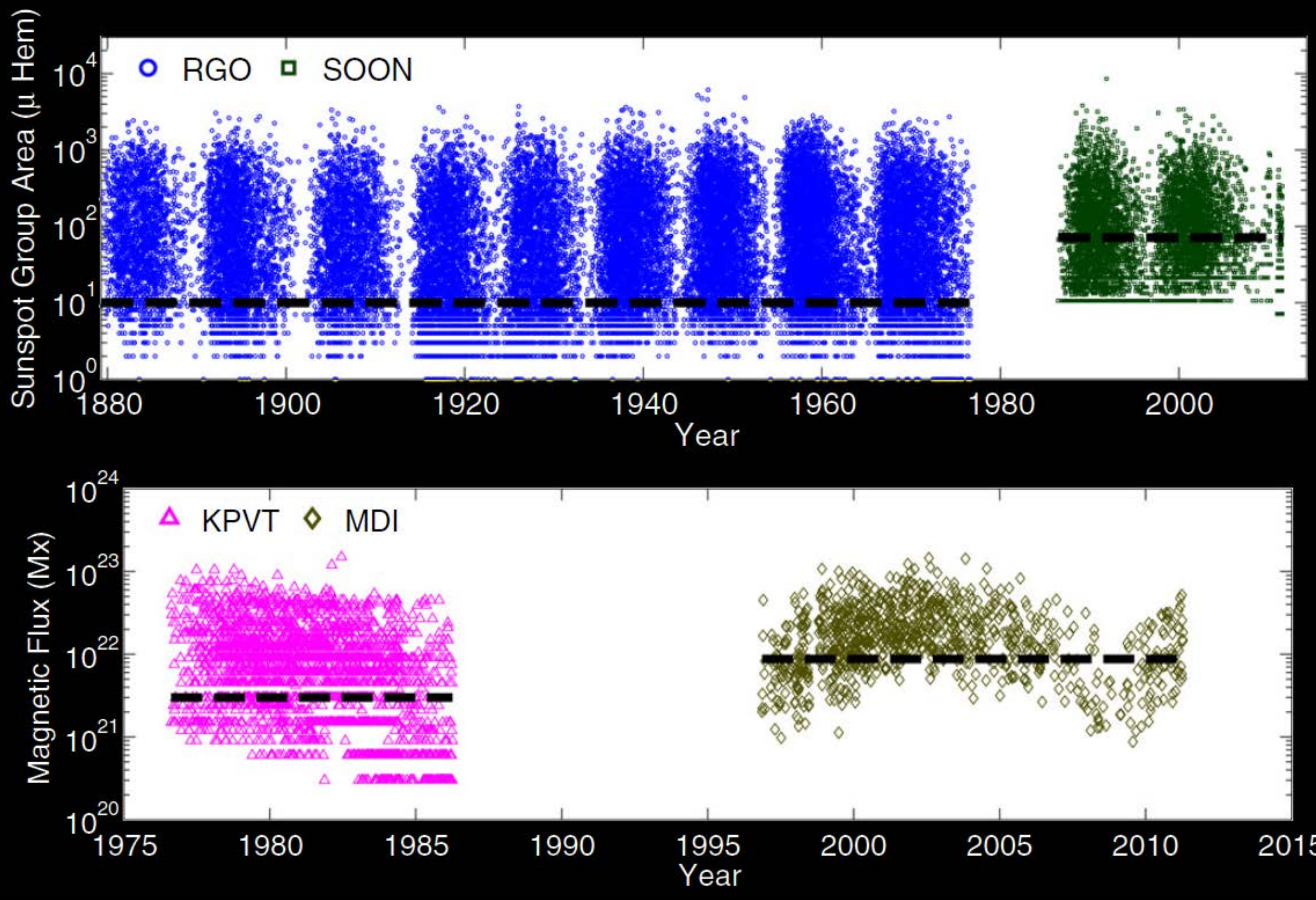
- Sunspot Group Area:
  - Royal Greenwich Observatory (RGO). 1874 - 1976.
  - Solar Observing Optical Network (SOON). 1985 - present.
  - Pulkovo's catalogue of solar activity (PCSA). 1938 - 1991.
  - Kislovodsk Mountain Astronomical Station (KMAS). 1954 - present.
  - SDO/HMI. 2010 - present.

- Sunspot Area:
  - SOHO/MDI Umbral. 1996 - 2010.
  - SDO/HMI Umbral. 2010 - present.
  - San Fernando Observatory (SFO). 1983 - present.

- Bipolar Magnetic Region Flux:
  - KPVT. 1976 - 1986.
  - SOHO/MDI. 1996 - 2010.
  - KPVT/SOLIS. 1996 - present.

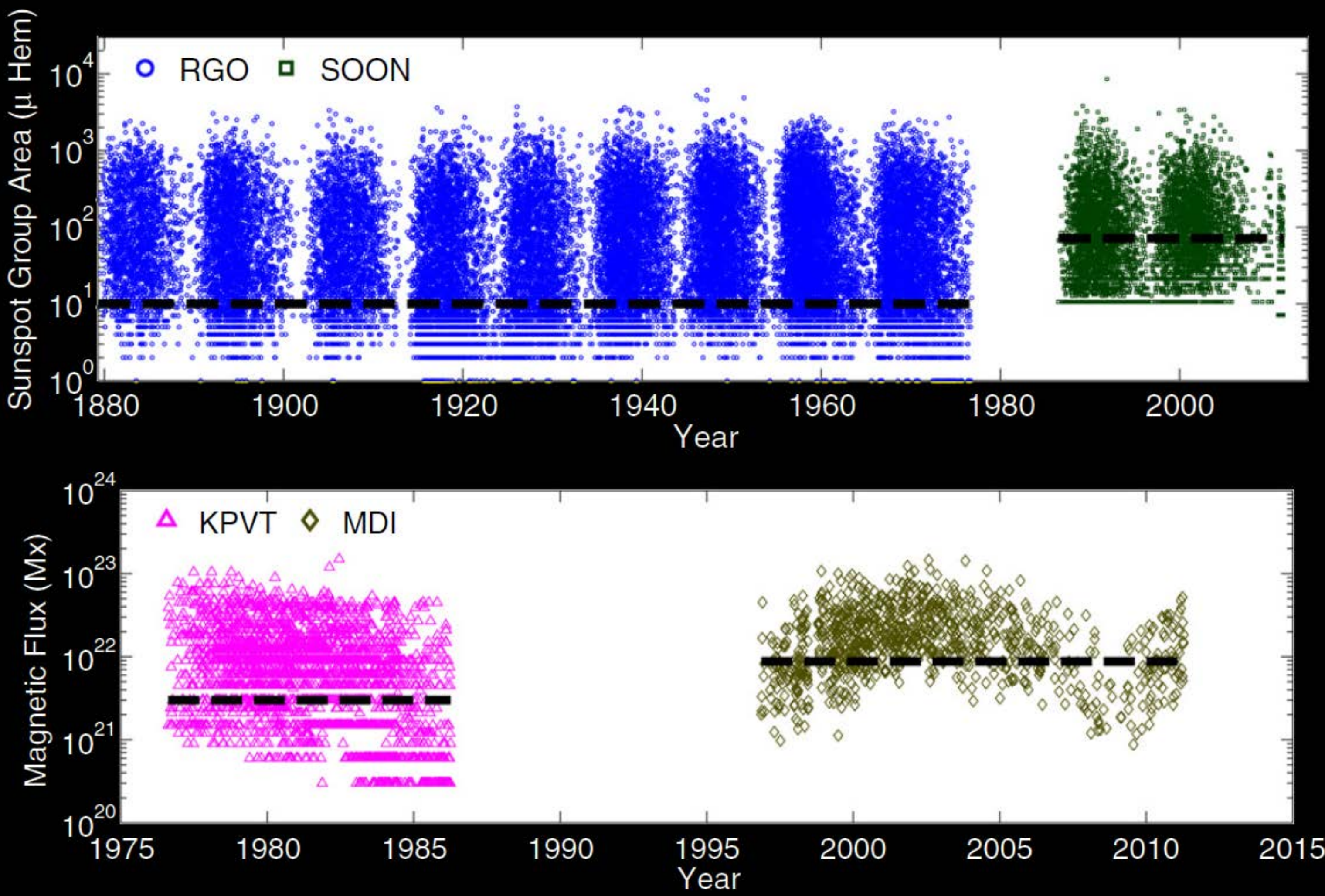
# Data Truncation

- Structures near the lower detection threshold suffer from a host of issues that can potentially distort our statistical analysis.



# Data Truncation

- To avoid this issues, we impose a truncation limit one order of magnitude above the minimum size of detection.



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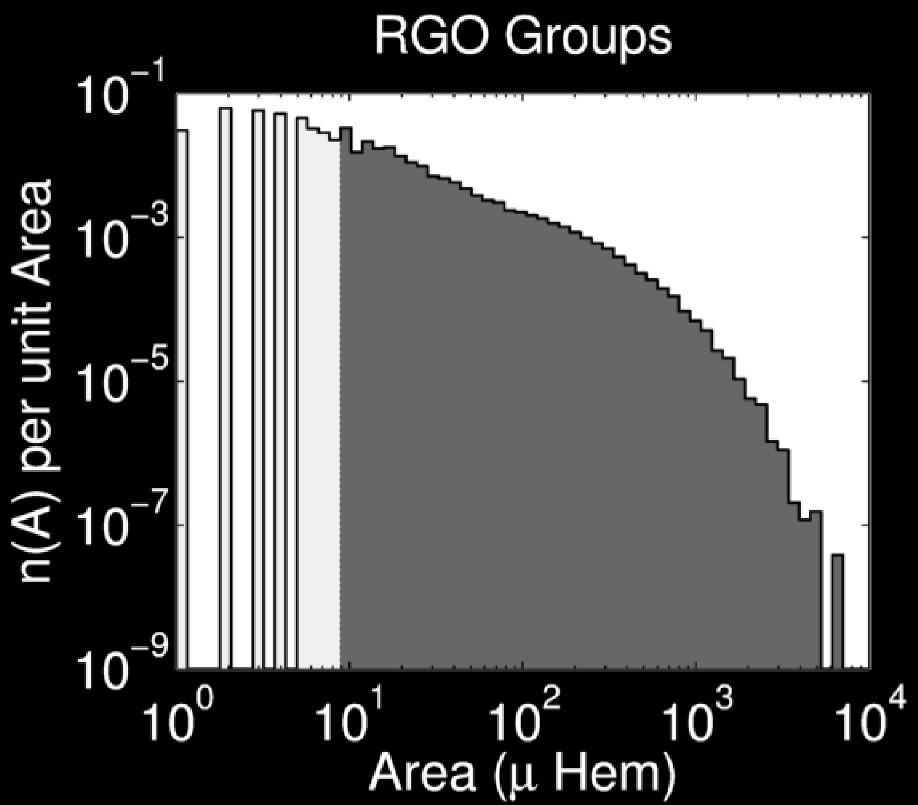



Only data inside dark areas is included in our fits and analysis, light areas are shown for visual reference.

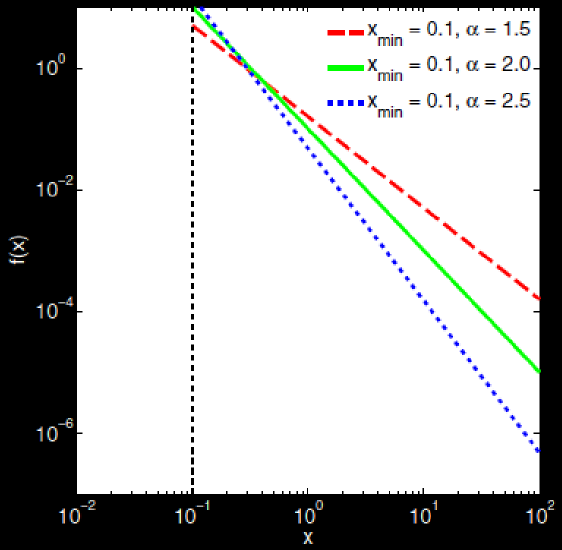
# AREA AND FLUX DISTRIBUTION

Muñoz-Jaramillo et al., *ApJ*, **800**:48, 2015

In collaboration with Ryan Senkpeil, John Windmueller, Ernest Amouzou, Dana Longcope, Andrey Tlatov, Yury Nagovitsyn, Alexei Pevtsov, Gary Chapman, Angela Cookson, Anthony Yeates, Fraser Watson, Laura Balmaceda, Piet Martens, & Ed DeLuca

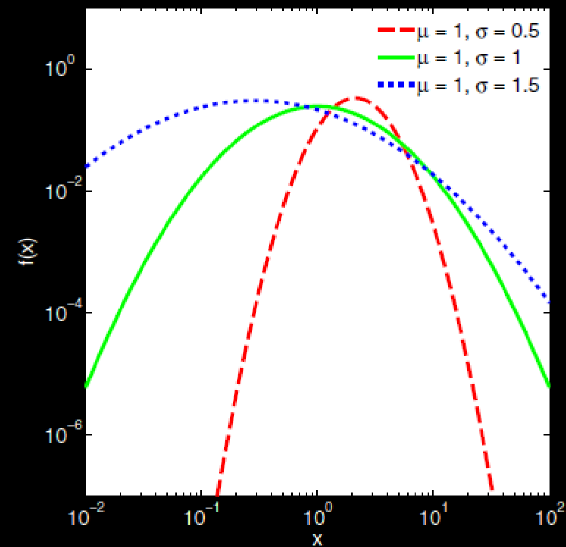
# Which distribution to use?

## Power Law



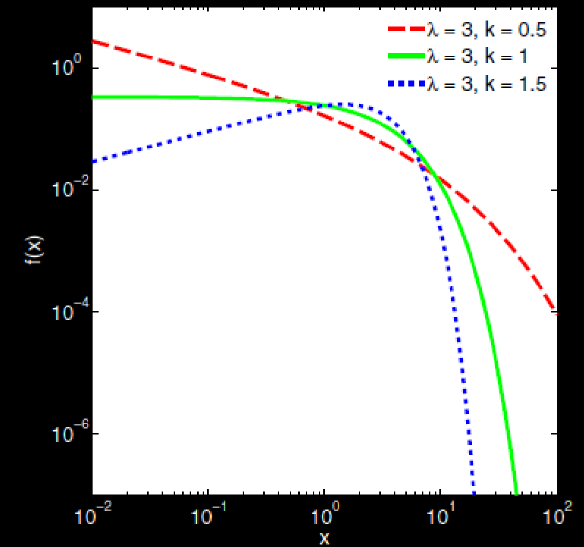

Zharkov et al. (2005)
Meunier (2003)
Hagenaar et al. (2003)
Parnell et al. (2009)

## Log-Normal




Bogdan et al. (1988)
Baumann & Solanki (2005)
Zhang et al. (2010)
Schad & Penn (2010)

## Weibull




Parnell (2002)

## Exponential

Tang et al. (1984)
Schrijver et al. (1997)

## Composite Distributions

Kuklin (1980)　Harvey & Zwaan (1993)　Jiang et al. (2011)　Nagovitsyn et al. (2012)

# Which distribution to use?

- We fitted our 11 databases with these four distributions (power-law, log-normal, Weibull, exponential), and a log-nomal-Weibull composite.

- We applied a quantitative model selection criterion called Akaike's Information Criterion (AIC; Akaike 1983):

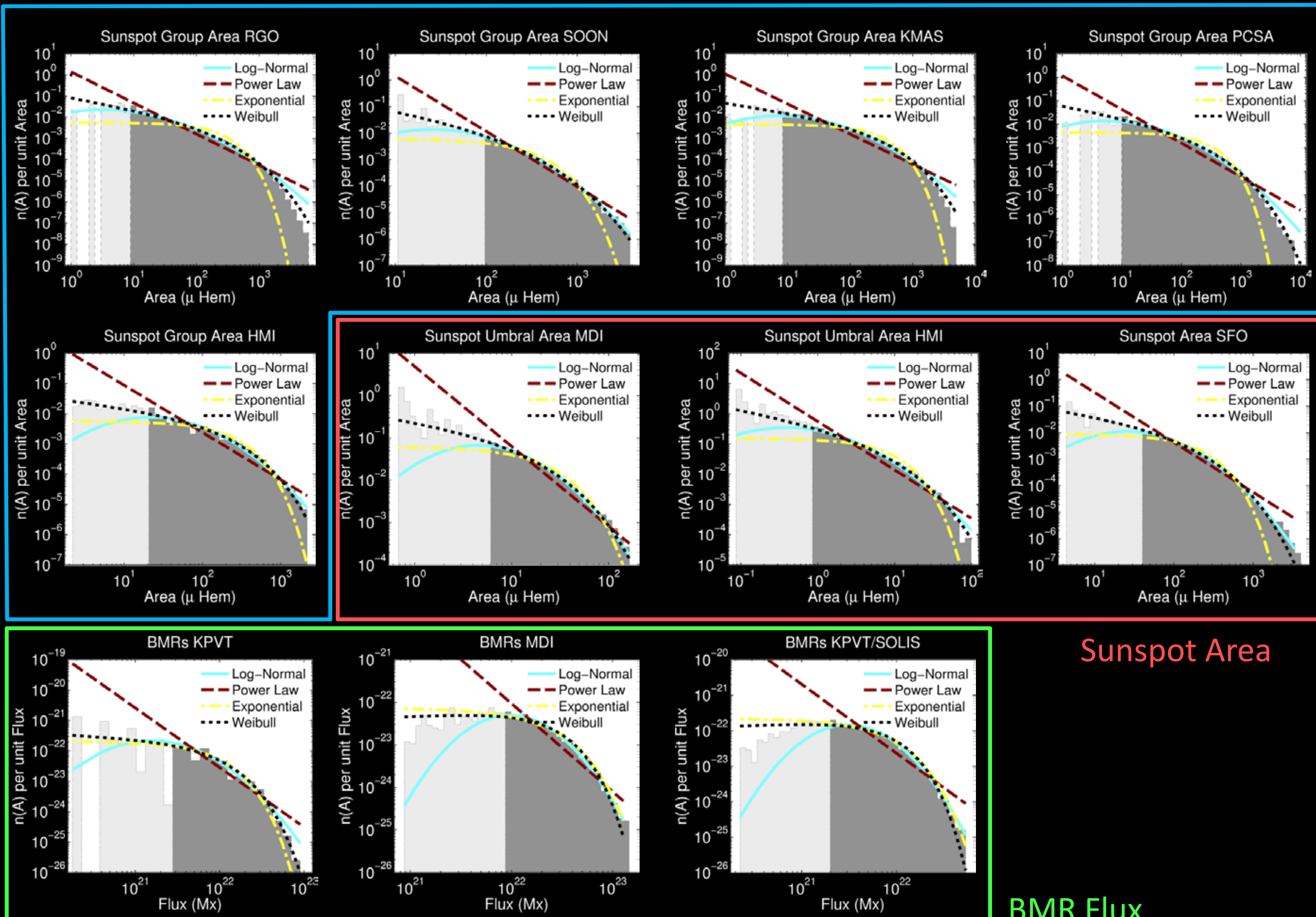
$$\mathrm{AIC} = -2\,\mathrm{lk}\left(M\right) - 2n$$

- In AIC, the model's log-likelihood (lk) and the fitted model's degrees of freedom (n) are used to strike a balance between underfitting and overfitting.

- AIC is a relative method of model discrimination, the **BEST** model is not necessarily the **"TRUE"** model.

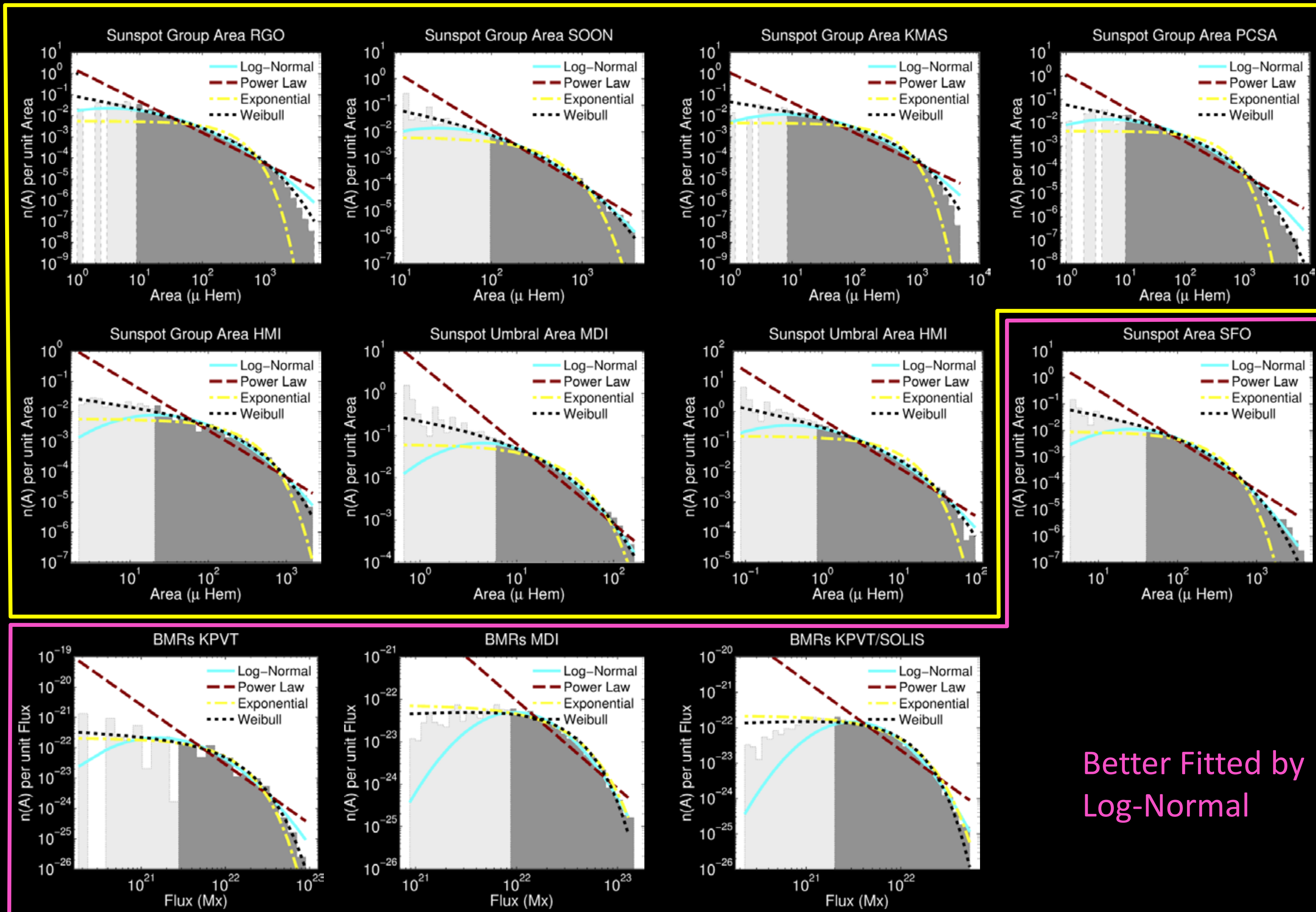
# Single Fits

Sunspot Group Area



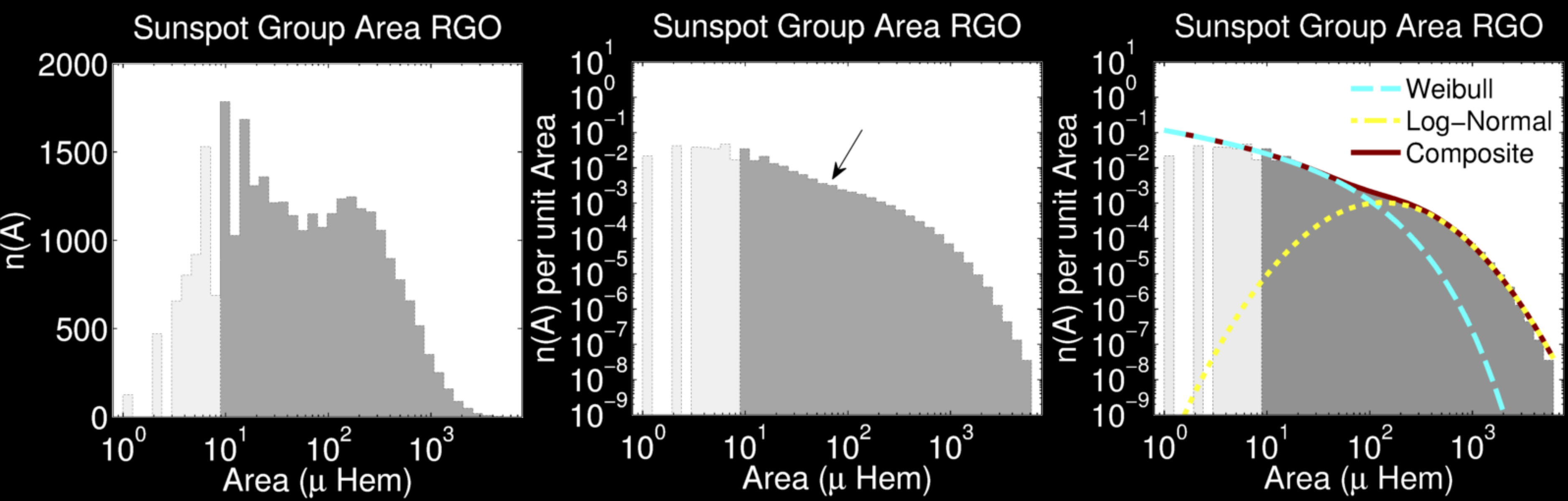
# Single Fits

Better Fitted by Weibull




Better Fitted by Log-Normal

# A combination of Weibull and Log-normal distributions fits the data best.




- Different sets are sampling different sections of a single distribution.
- Conflicting results arise from different data types sampling different part of this distribution.

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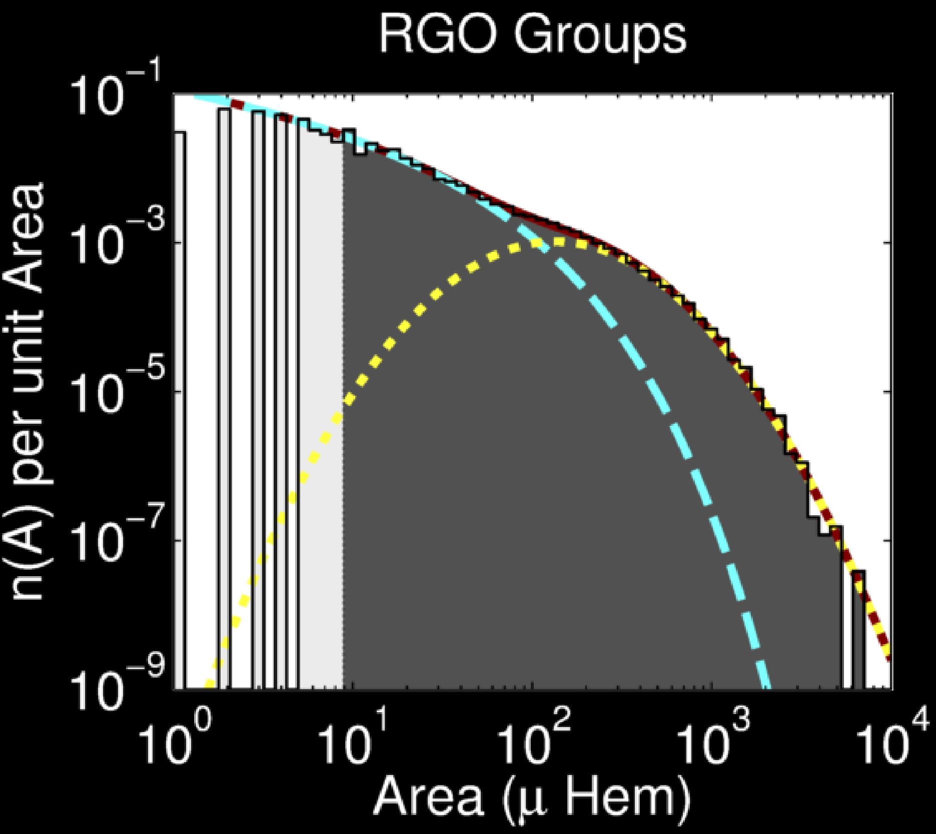


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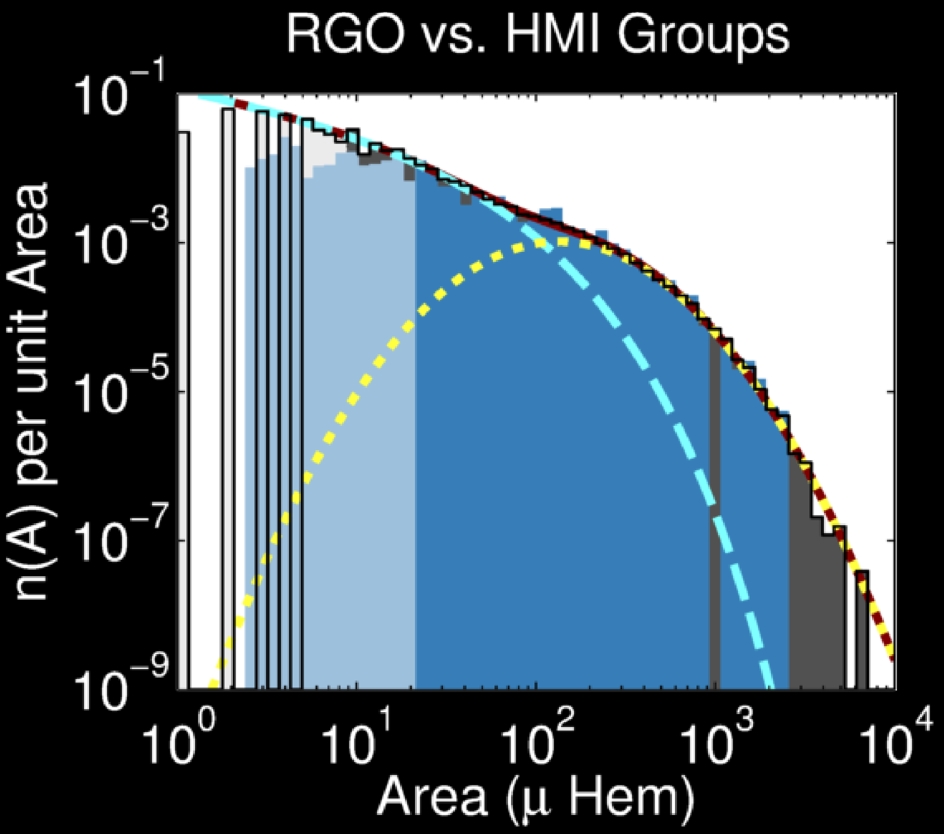


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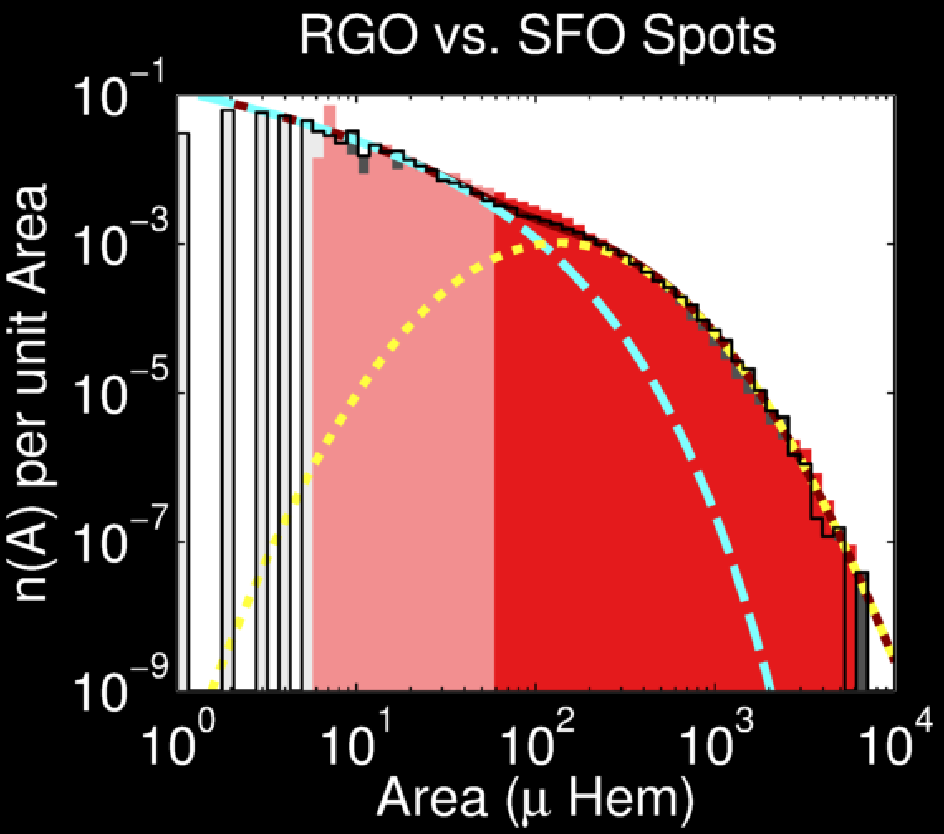


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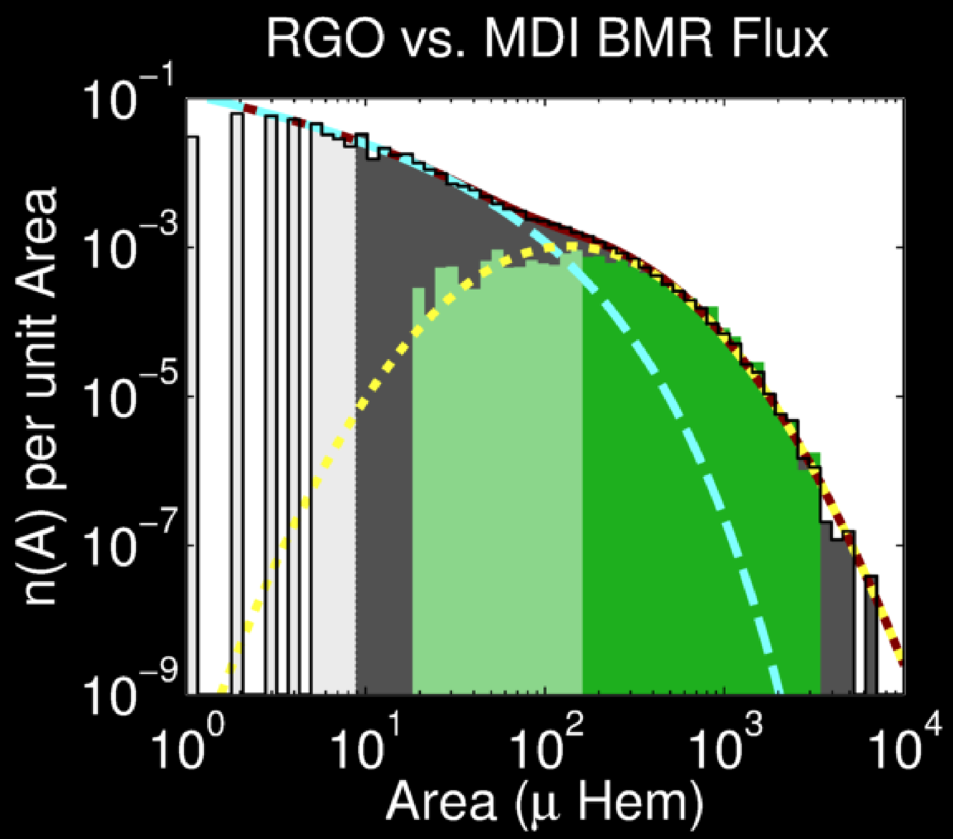


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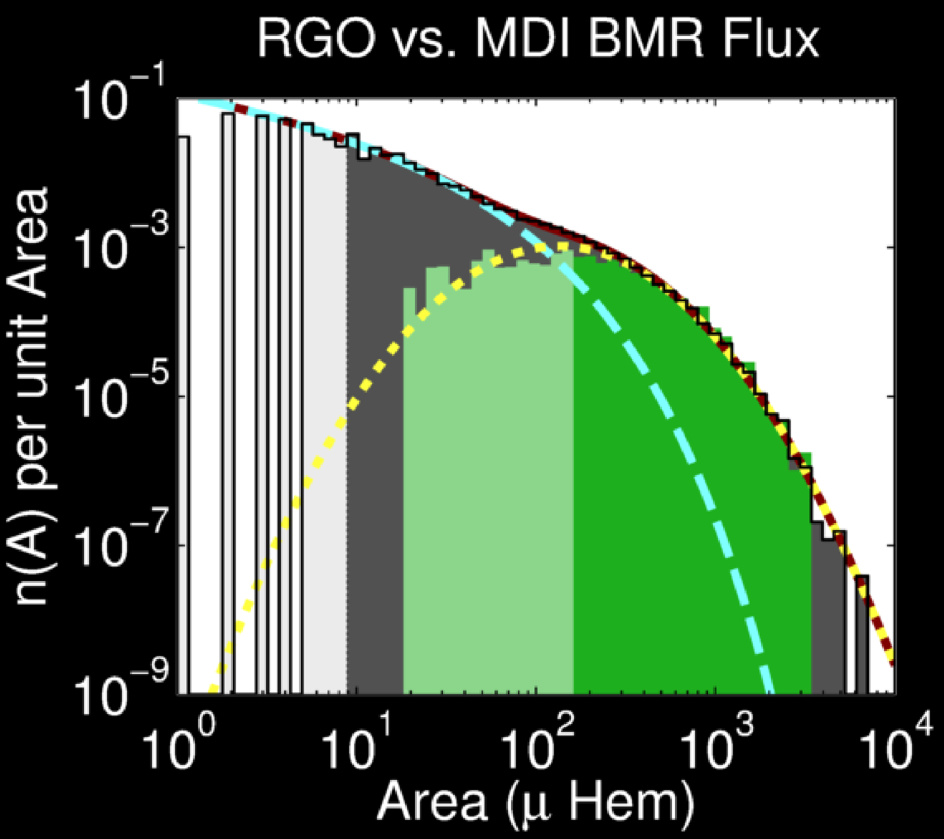


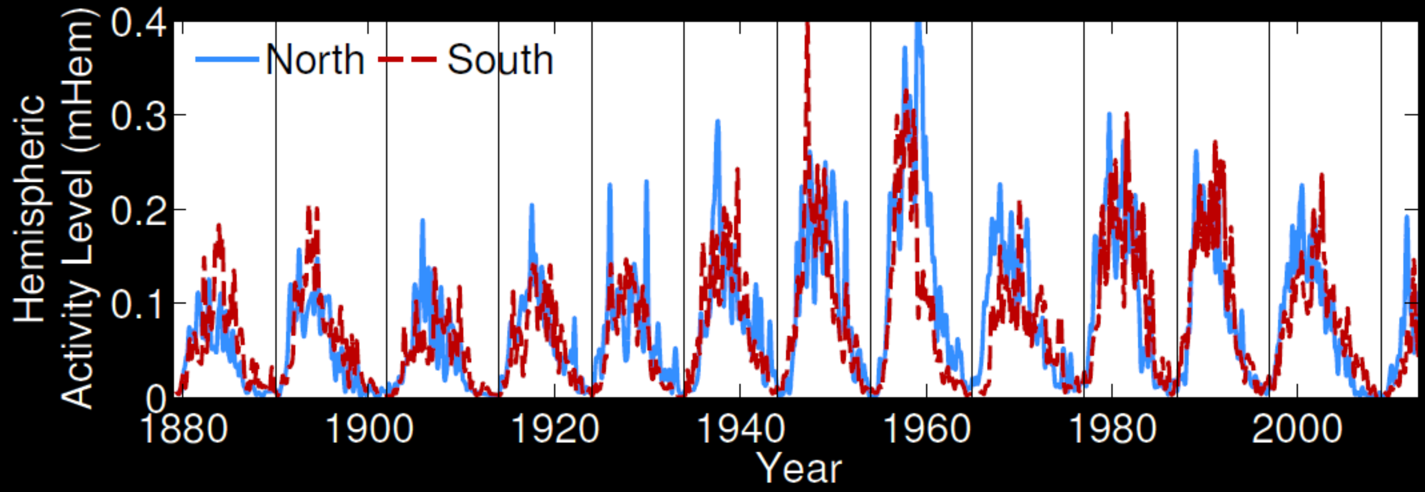

- The log-normal component is populated by the largest sunspot groups/BMRs, the Weibull component by small pores.

# CYCLE DEPENDENCE OF SUNSPOT GROUP PROPERTIES

Muñoz-Jaramillo et al., *ApJ*, **in press**, 2015

In collaboration with Ryan Senkpeil, Dana Longcope, Andrey Tlatov, Alexei Pevtsov, Piet Martens, & Ed DeLuca

# Activity Level:
# A New Way of Binning Data




- Cycle evolution of active regions and sunspots is normally studied by comparing separate cycles or phases (minimum vs. maximum).

- This approach is sub-optimal for studying sunspot and BMR properties. Why?

# Activity Level:
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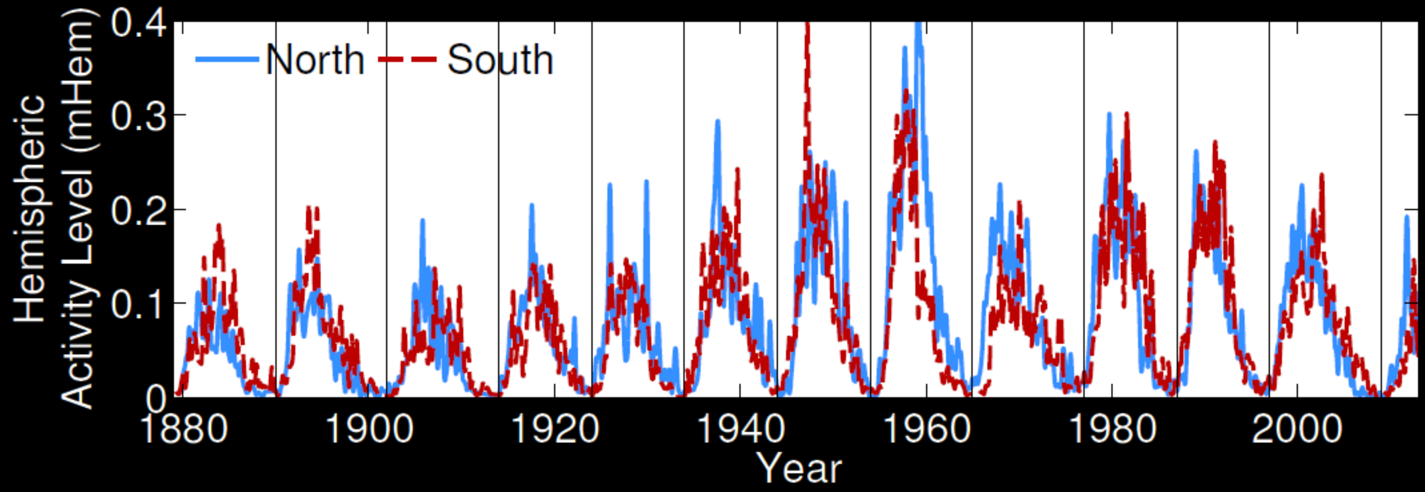


- **The lifetime of an active region is but an instant compared with the cycle.**

- **Assumption: The global properties of a cycle are irrelevant for determining the properties of active regions. Only activity level is important.**

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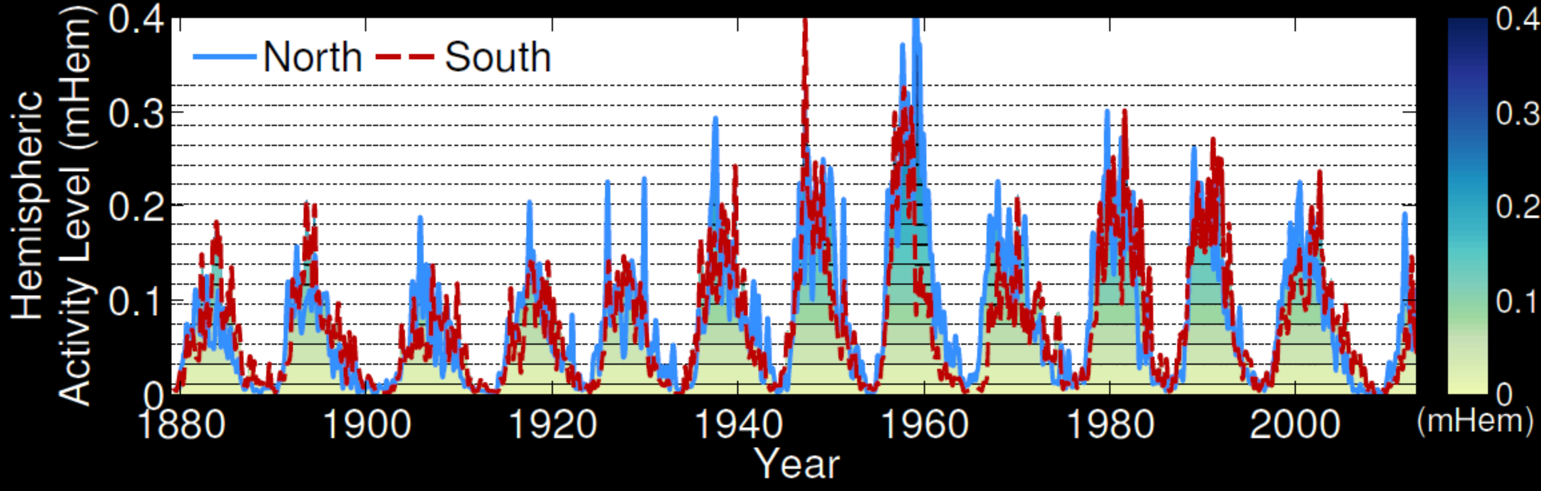


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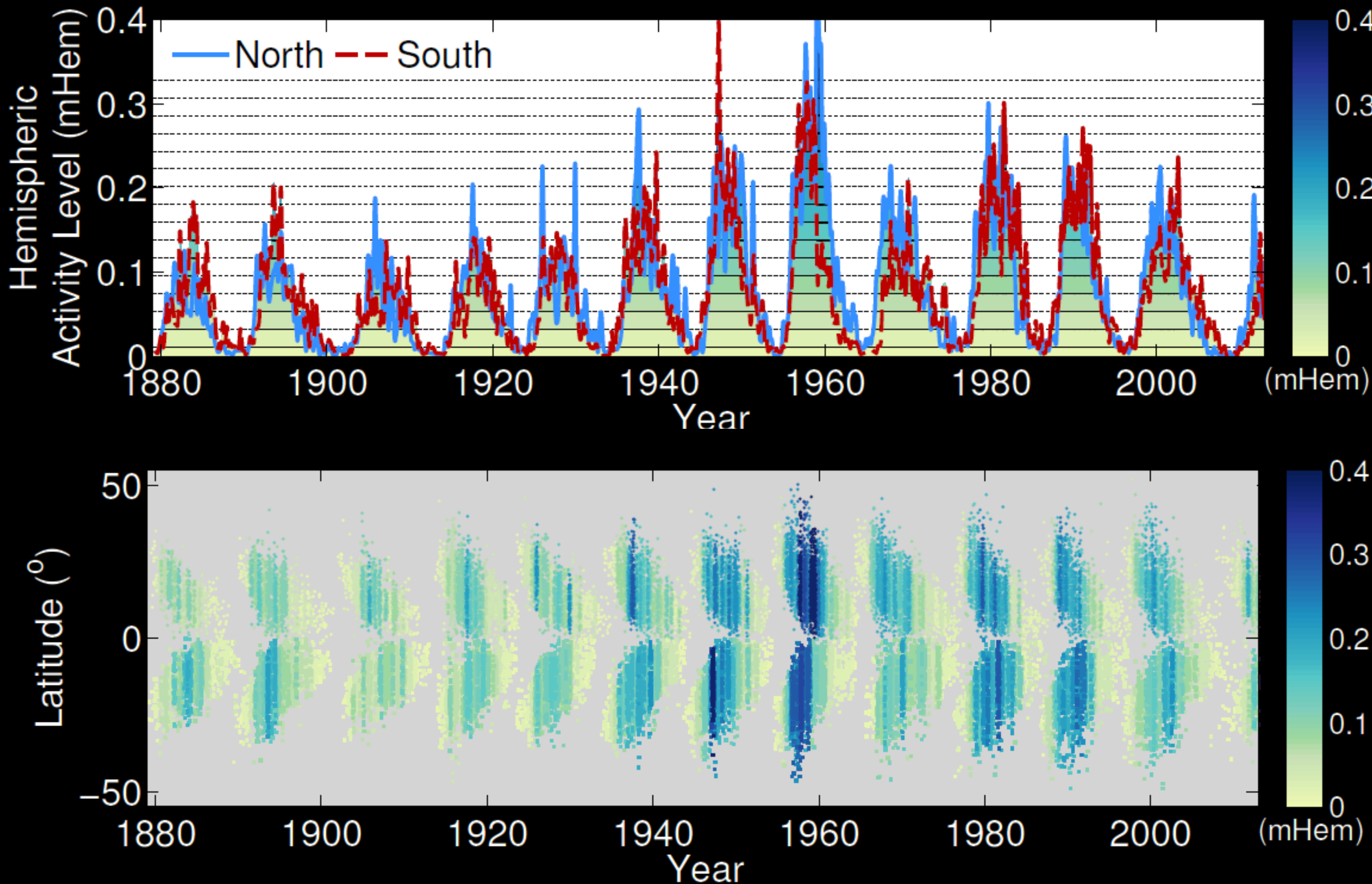
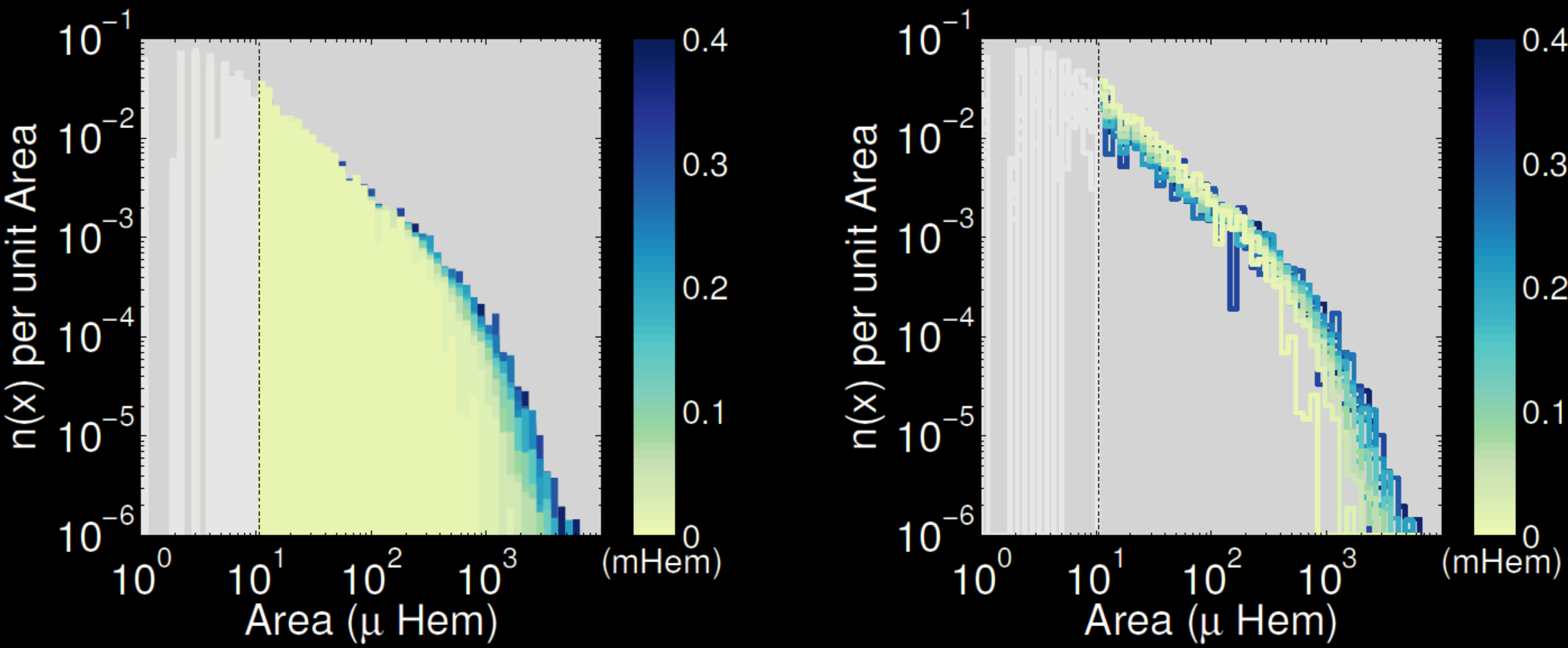


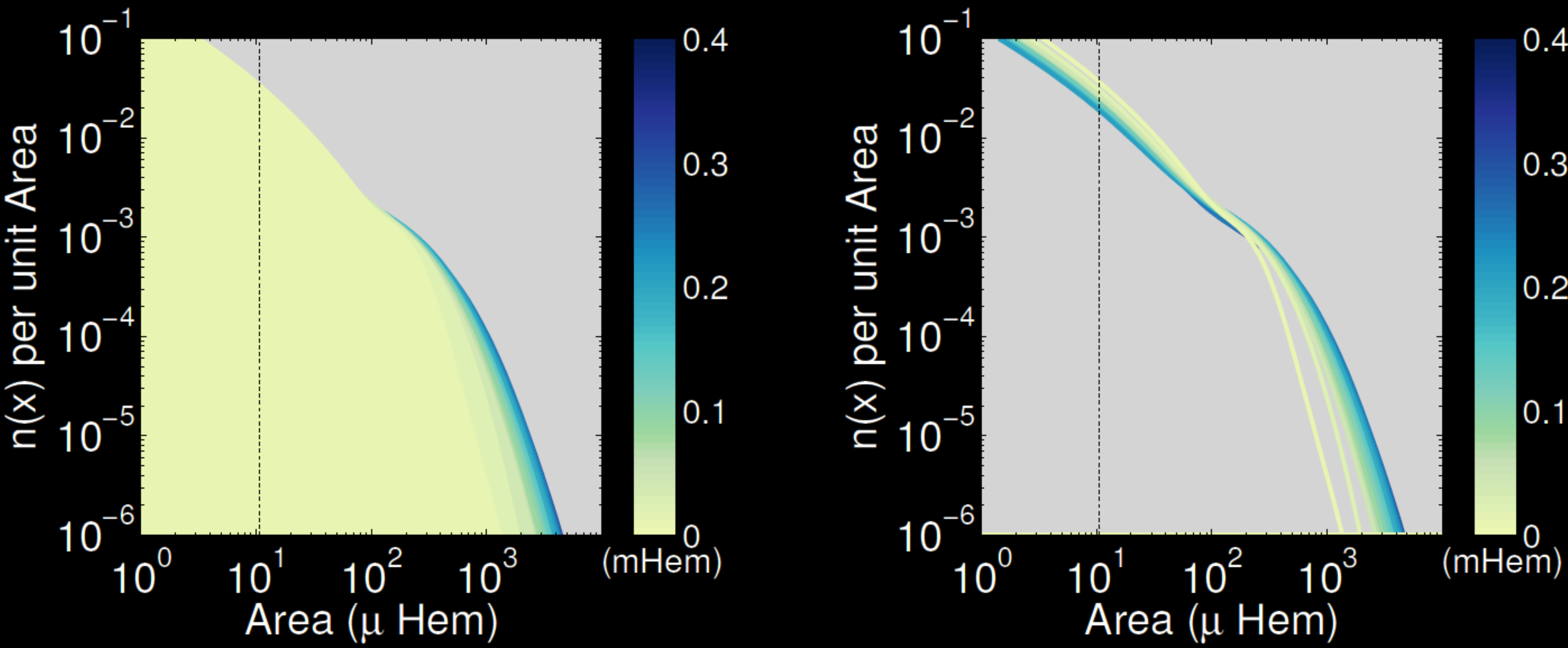

Statistical properties associated with low activity levels are observed in every cycle. Statistical properties can be different in each hemisphere.

# Activity Level and the empirical distribution function




- There is a very clear dependence of the relative amount of large sunspot groups and higher activity levels.
- The Weibull-Log-Normal composite captures successfully this variation

# Activity Level and the empirical distribution function

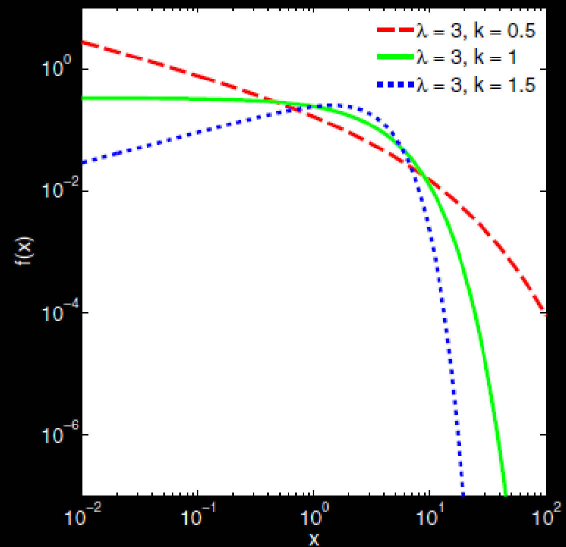



- There is a very clear dependence of the relative amount of large sunspot groups and higher activity levels.
- The Weibull-Log-Normal composite captures successfully this variation

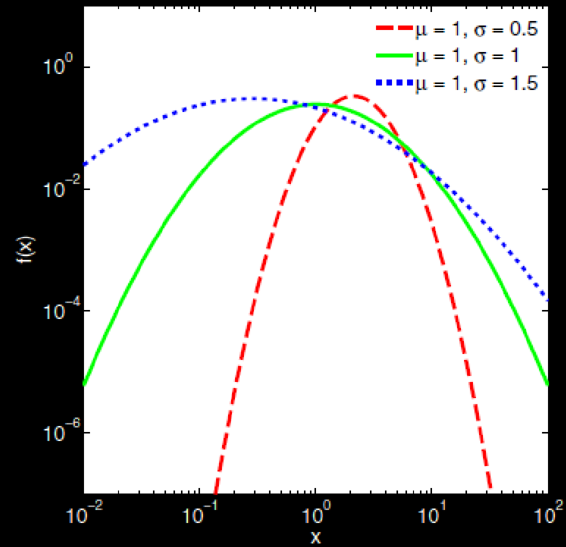
# Activity level and the analytic probability density function

$$f(x\,|\,k,\lambda,\mu,\sigma,c)=(1-c)\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}}+\frac{c}{x\sigma\sqrt{2\pi}}e^{-\frac{(\ln x-\mu)^{2}}{2\sigma^{2}}}$$

Weibull




Log-Normal




Scale Factor (λ)

Mean (μ)

Shape Parameter (k)

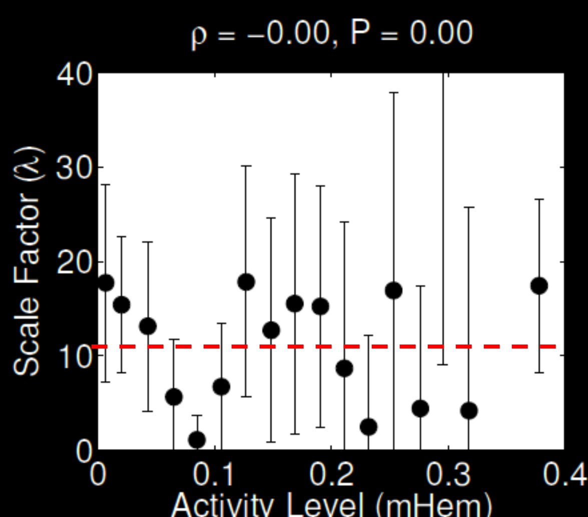
Variance (σ)

# Activity level and the analytic probability density function

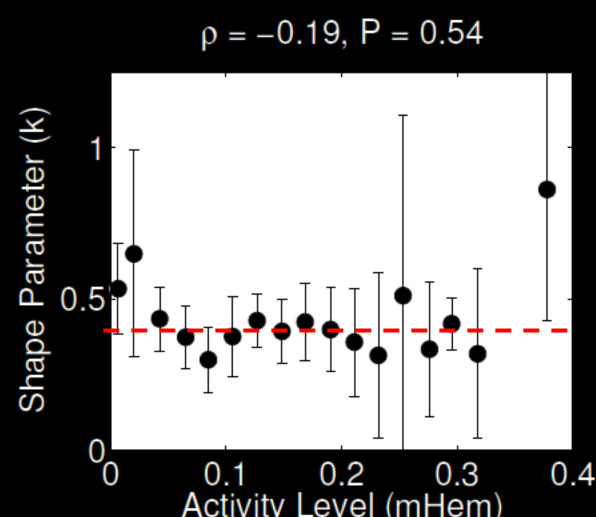
$$f(x\,|\,k,\lambda,\mu,\sigma,c) = (1-c)\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}} + \frac{c}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$$

- The Weibull's parameters are not correlated activity level (Hagenaar et al 2003, 2008).

Scale Factor ($\lambda$)




Shape Parameter (k)



# Activity level and the analytic probability density function

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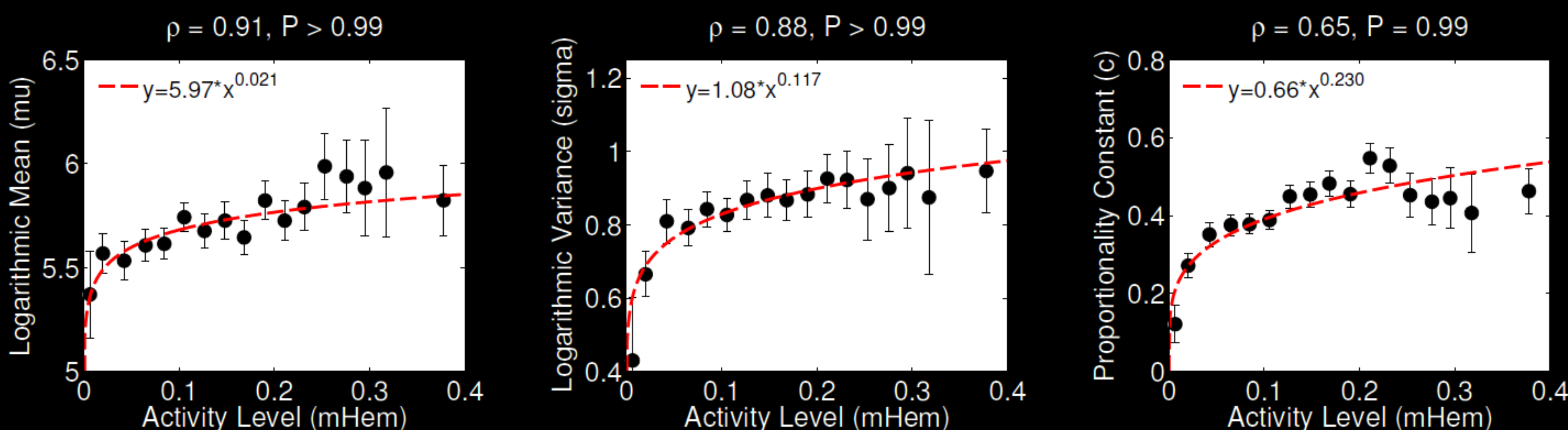
- The Log-Normal parameters correlate strongly with activity level

Mean ($\mu$) Variance ($\sigma$) Proportionality ($c$)



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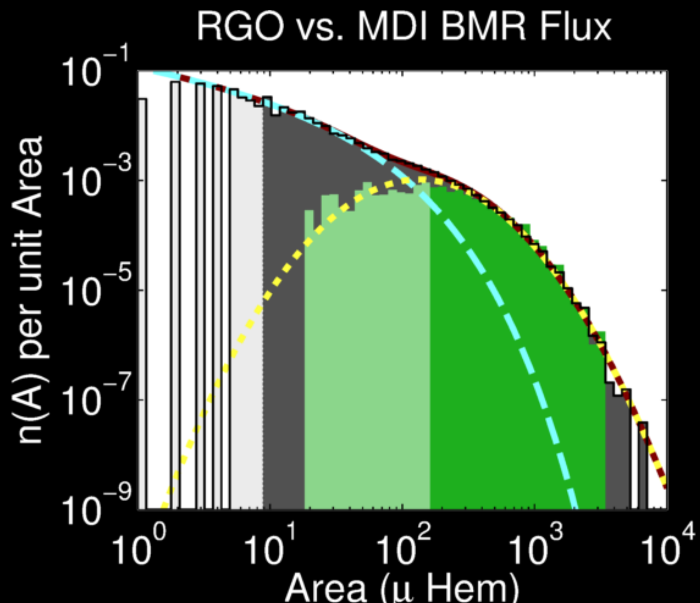


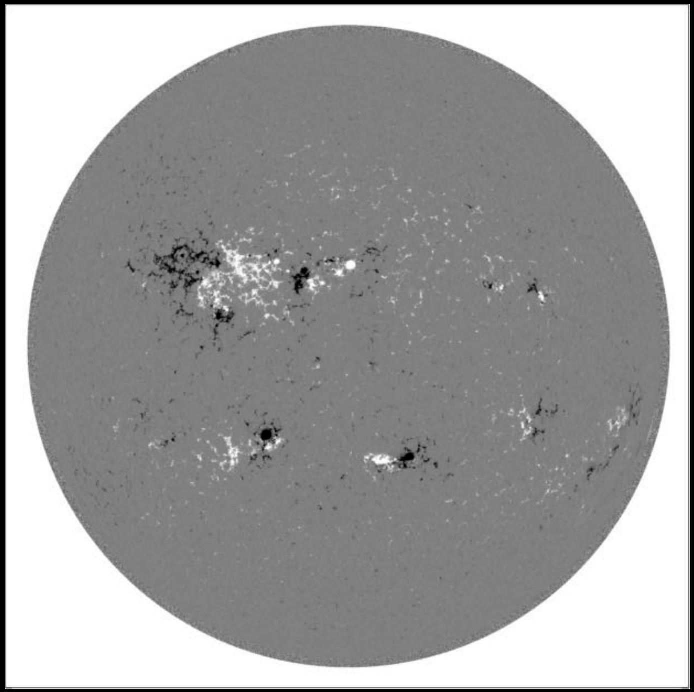

- Cycle-dependent variations of the size-flux distribution are dictated exclusively by the large BMRs!

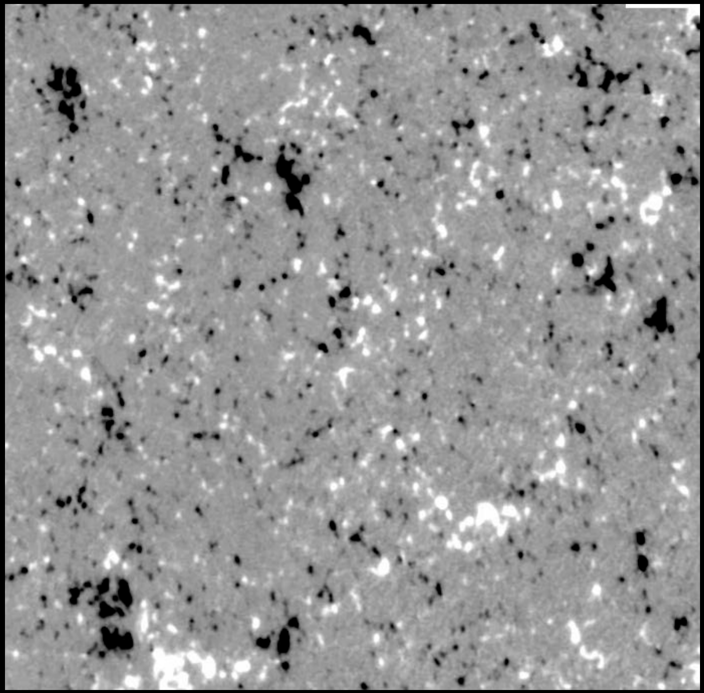
# IMPLICATIONS

When I submitted my abstract I thought I understood what these results meant.

This is not the case anymore

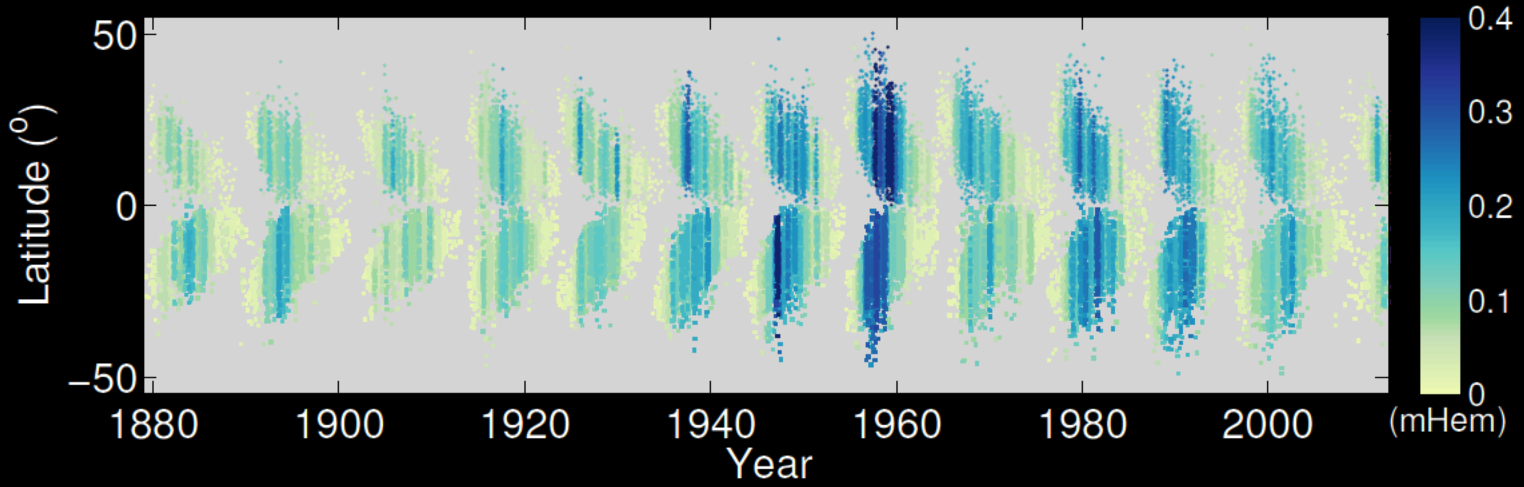
# Small-scale vs. Global Dynamo?





- In our first paper we speculated that the structures associated with each component were associated with different forms of dynamo action.

# ~~Small-scale vs. Global Dynamo?~~




- **Sunspot groups and pores are only observed in active latitudes (spatial dependence on cycle evolution).**
- **Why are the statistical properties of pores fixed?**

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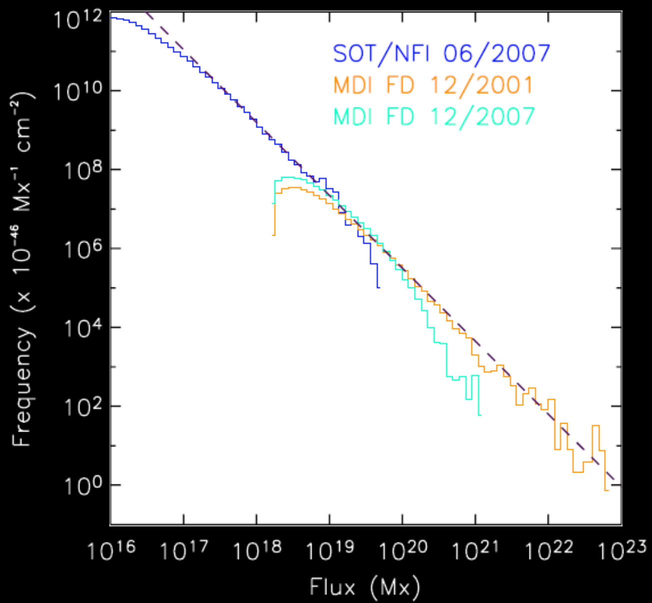


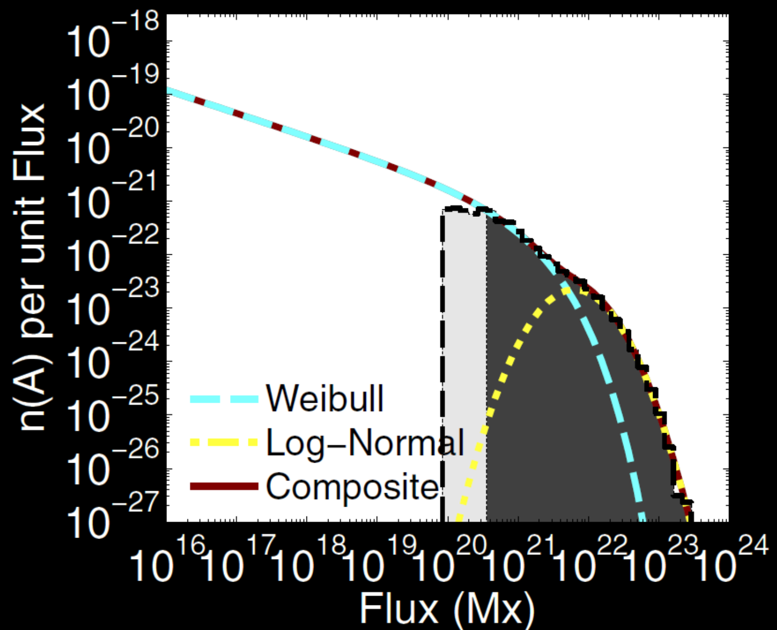


- Sunspot groups and pores are only observed in active latitudes (spatial dependence on cycle evolution).
- Why are the statistical properties of pores fixed?
  - Self-similarity driven by convection?
  - Separate originating mechanisms?

# Concluding Remarks

- The solar size-flux distribution is a composite of Weibull and log-normal distributions. A very simple modulation of its parameters captures cycle dependence.
- Only the parameters that characterize the log-normal distribution change with activity level.
- Our results seem robust and significant, but I have little understanding of the underlying mechanisms.
- Analysis of magnetic data, and of MHD simulations will be critical for furthering our understanding.