

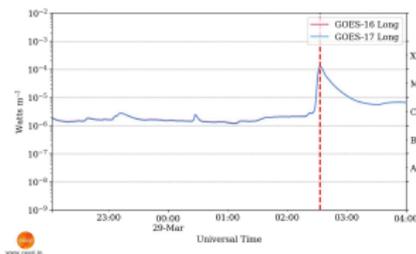
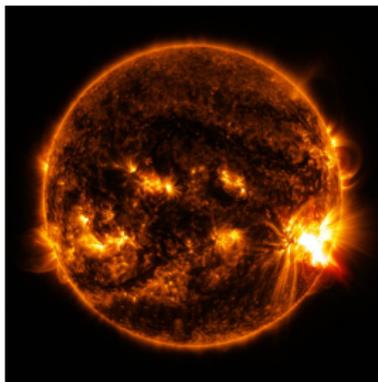
Statistical Properties of Solar Flare Dependency

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What are solar flares?



Solar flares are characterized by a large eruptions of electromagnetic radiation from the Sun. Solar flares can cause:

- Radio blackouts
- Increased radiation exposure to pilots
- Albeit rare, computer malfunctions

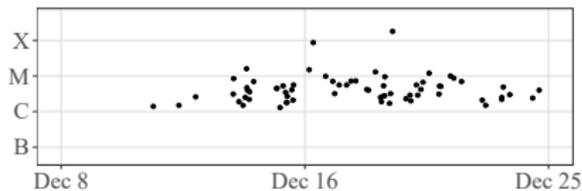
Motivation

Solar flares are difficult phenomena to predict due to their rarity. As a result, machine learning methods are becoming more prevalent within the field of solar flare prediction.

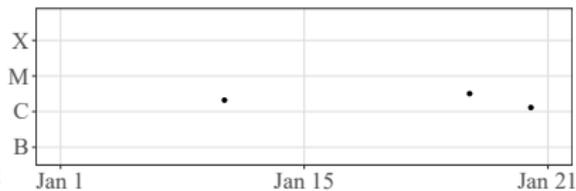
- Regression
- Neural Network
- Decision Tree Learning
- Support Vector Machines

Solar Flares

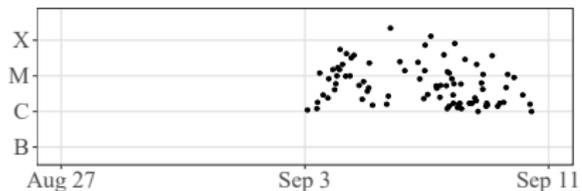
AR 4920



AR 1309



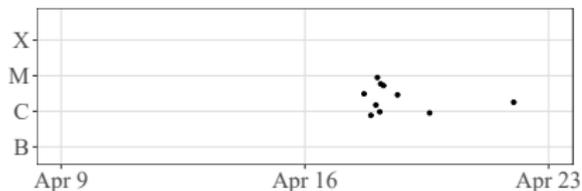
AR 7115



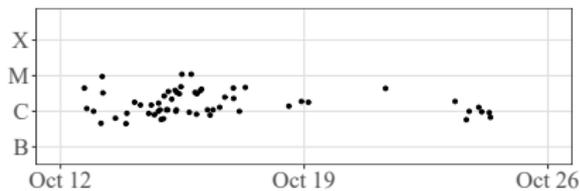
AR 1300



AR 1558



AR 6015

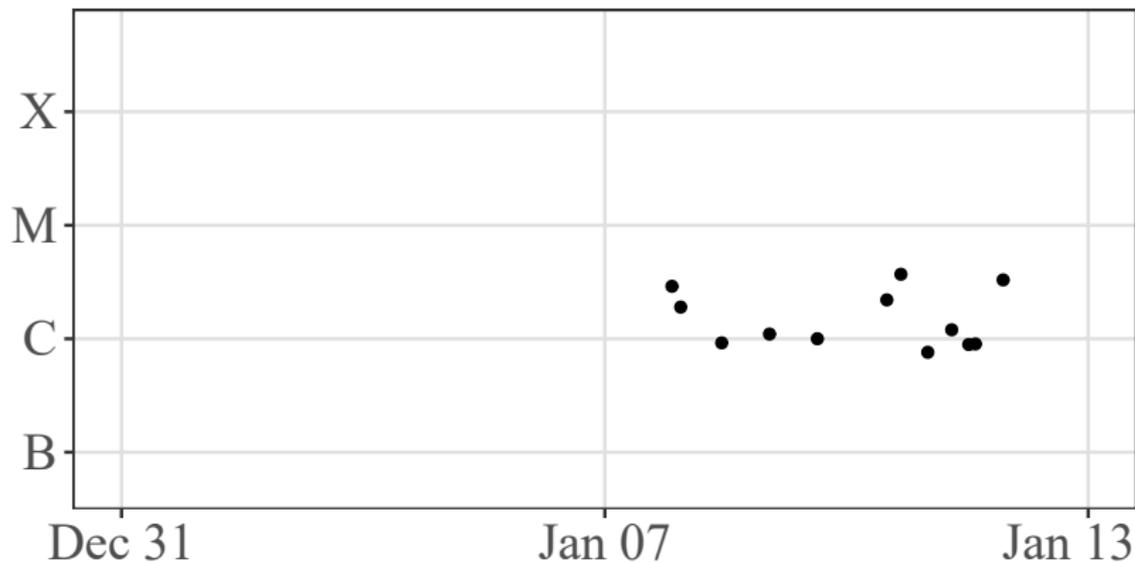


Main Research Question

What is the dependency structure that solar flares exhibit when coming from a single active region?

Active Region 1275

AR 1275



One Hypothesis to Test

H_0 : Flares that occur within 6 hours of each other are **independent**.

H_1 : Flares that occur within 6 hours of each other are **dependent**.

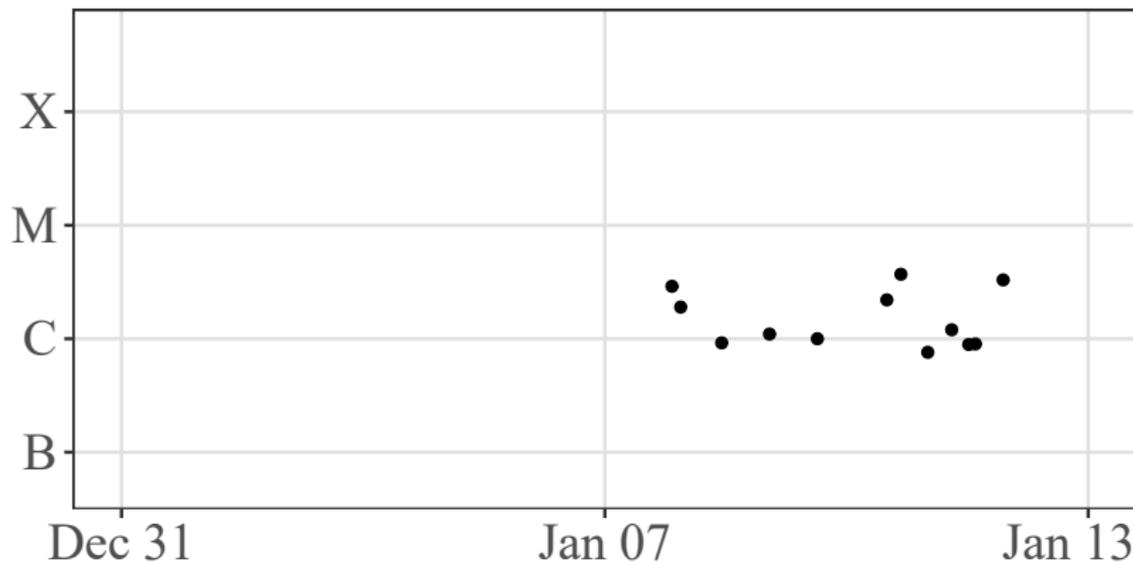


H_0 : $\mathbb{1}_{\text{Flare in next 6 hours}} \perp \mathbb{1}_{\text{Flare in previous 6 hours}}$

H_1 : $\mathbb{1}_{\text{Flare in next 6 hours}} \not\perp \mathbb{1}_{\text{Flare in previous 6 hours}}$

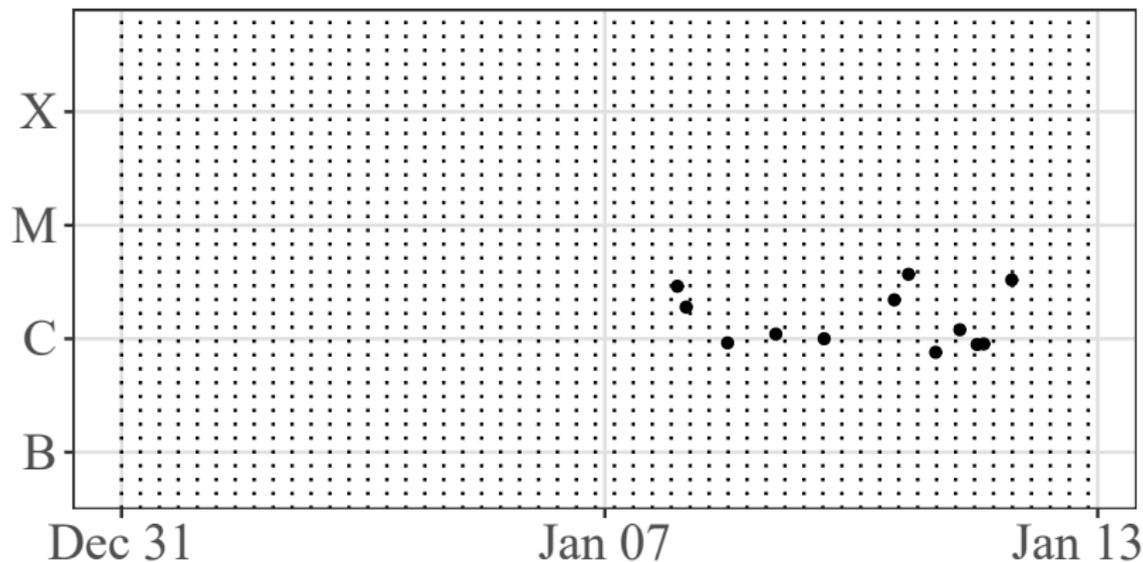
Active Region 1275

AR 1275



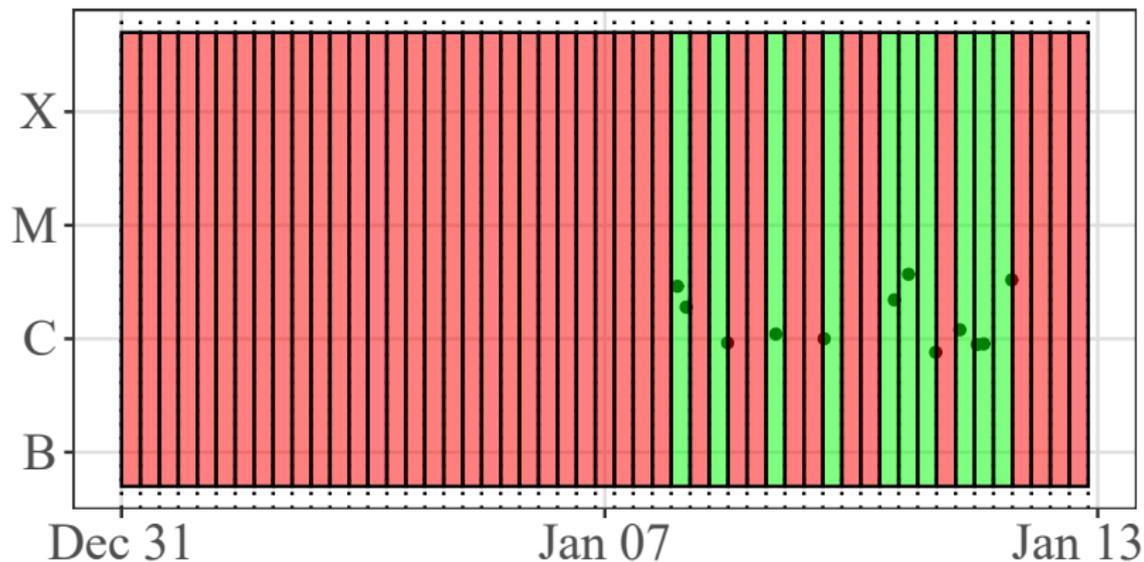
Active Region 1275

AR 1275



Active Region 1275

AR 1275



Active Region 1275

Collecting all samples from this active region, we get the following table summarizing the data,

	No flare in next 6 hours	Flare in next 6 hours
No flare in previous 6 hours	36	6
Flare in previous 6 hours	6	4

Using the typical χ^2 Test of Independence, yields a p-value of 0.1592.

U-Statistic Permutation Test

What about other tests? If we un-summarize our data, it would look something like this,

Flare in previous 6 hours	Flare in next 6 hours
0	0
1	1
⋮	⋮
1	1
1	0

Under the null, these two variables are independent.

U-Statistic Permutation Test

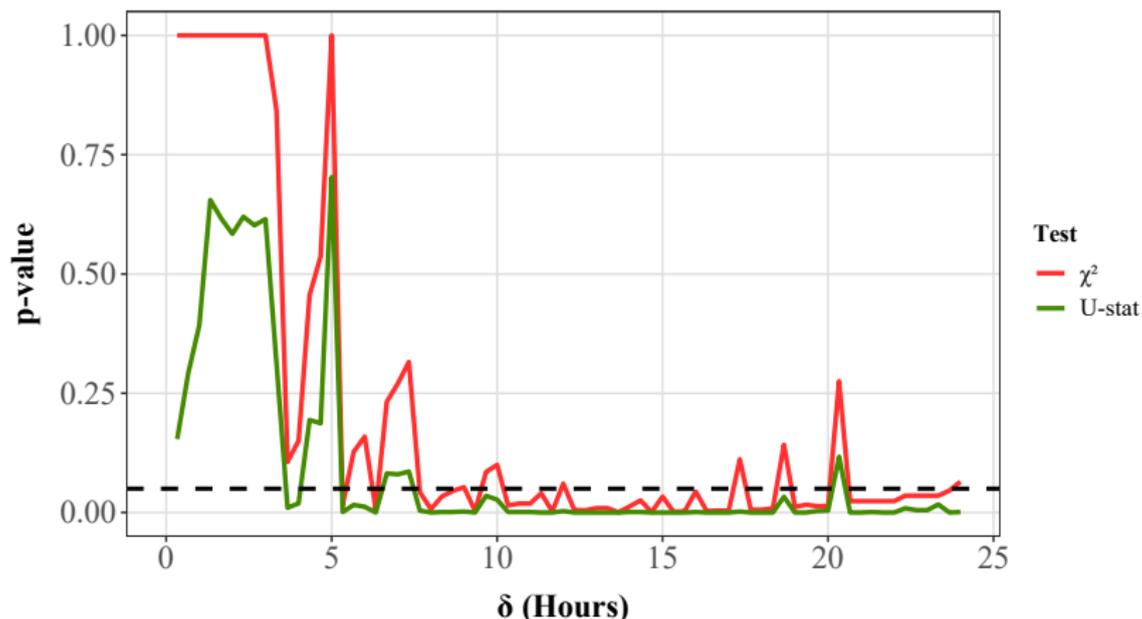
- Permute the first column of the data.
- Compute $b_n = \sum_{i,j} (\text{observed}_{i,j} - \text{expected}_{i,j})^2$
- Repeat this process, N times, and compare our observed table to the distributions of b_1, b_2, \dots, b_N

⇒ Doing this for active region 1275 yields a p-value of 0.0128.

Generalizing to δ time interval

For AR 1275, instead of considering a single time interval, we can vary the time considered.

Results from Hypothesis Testing
AR 1275 across different time intervals (δ)



Flare Catalogue

The previous process done for a catalogue consisting of:

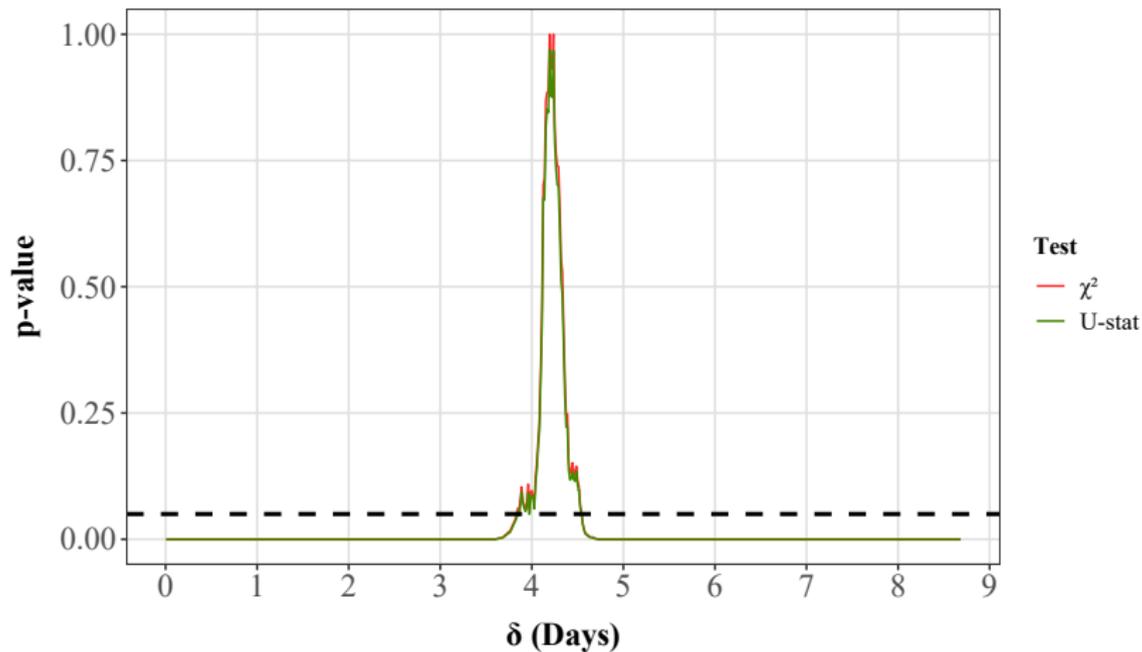
- Roughly an entire solar cycle
- 12,496 solar flares
- 1,044 active regions

Furthermore, we break the testing into homogeneous and heterogeneous results.

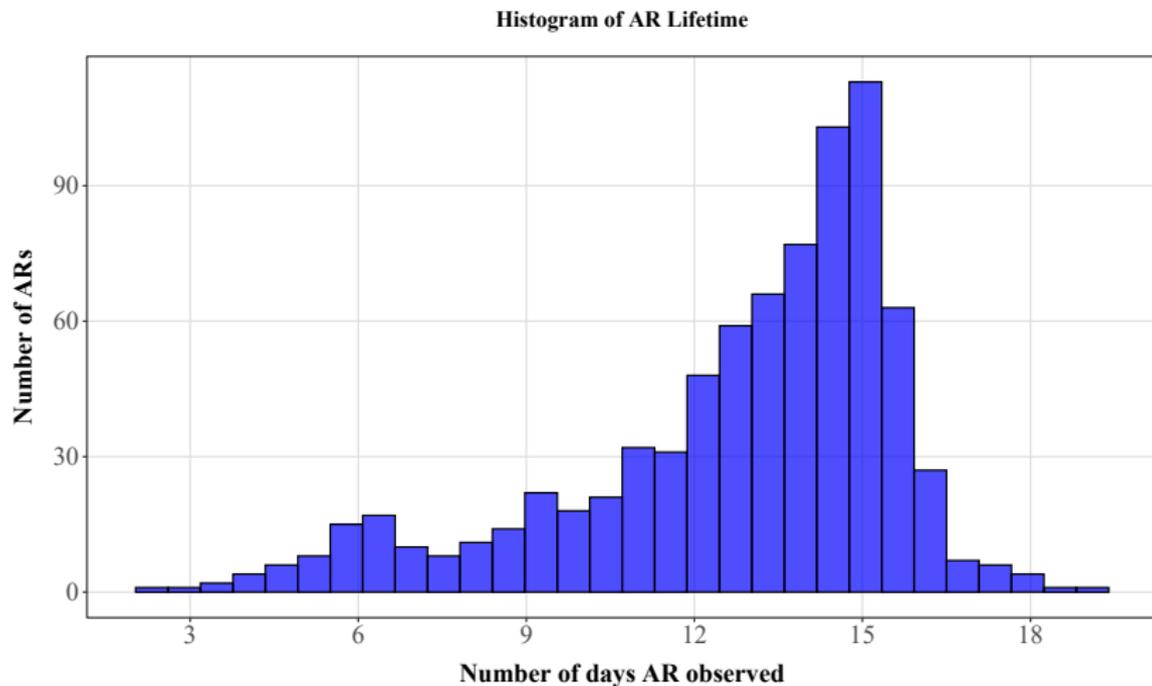
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:Product: 20050316events.txt
:Created: 2005 Mar 17 1802 UT
:Date: 2005 03 16
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Environment Center.
# Please send comments and suggestions to SEC.Webmaster@noaa.gov
#
# Missing data: ////
# Updated every 30 minutes.
#
# Edited Events for 2005 Mar 16
#-----#
#Event  Begin  Max  End  Obs  Q  Type  Loc/Frq  Particulars  Reg#
#-----#-----#-----#-----#-----#-----#-----#-----#-----#
1590    0318  0318    0318  LEA  G  RBR  245      51
1620 +   0348  ////    1635  COM  C  RSP  30-80    CTM/1
1600 +   0408  0410    0412  LEA  G  RBR  245     210
1730 +   0422  1214    1511  COM  G  RNS  245     160
1610    0522  0528    0532  G10  5  XRA  1-8A    B4.2  1.9E-04
1630    0741  0744    0748  G10  5  XRA  1-8A    B1.9  7.3E-05
1630    0741  ////    0743  SVI  C  RSP  025-089 III/1
1640    1052  ////    1053  SVI  U  RSP  025-046 III/1
1650    1125  1125    1125  SVI  G  RBR  245     85
1650    1125  1125    1125  SVI  G  RBR  410     46
1660    1150  ////    1150  SVI  C  RSP  025-041 III/1
1670 +   1205  1208    1210  G12  5  XRA  1-8A    B3.5  8.1E-05  0742
1670    1206  1206    1209  SAG  G  RBR  245     100  0742
1670    1207  1207    1207  SAG  G  RBR  410     56  0742
1670    1209  1210    1210  G12  5  XFL  S02M48  3.0E+02 6.5E+02 0742
1670    1210  ////    2228  SAG  C  RSP  110-180 CTM/1
1680 +   1217  1221    1223  G12  5  XRA  1-8A    B5.1  1.4E-04 0742
1680 +   1219  1219    1219  SVI  G  RBR  410     310 0742
1680    1221  1222    1223  G12  5  XFL  S03W50  7.5E+02 2.3E+03 0742
1690 +   1242  1245    1247  G12  5  XRA  1-8A    B3.1  7.7E-05 0742
1690    1246  1246    1247  G12  5  XFL  S07W48  4.3E+02 9.1E+02 0742
```

Homogeneous Results

Homogeneous Results across different time intervals (δ)



Homogeneous Results



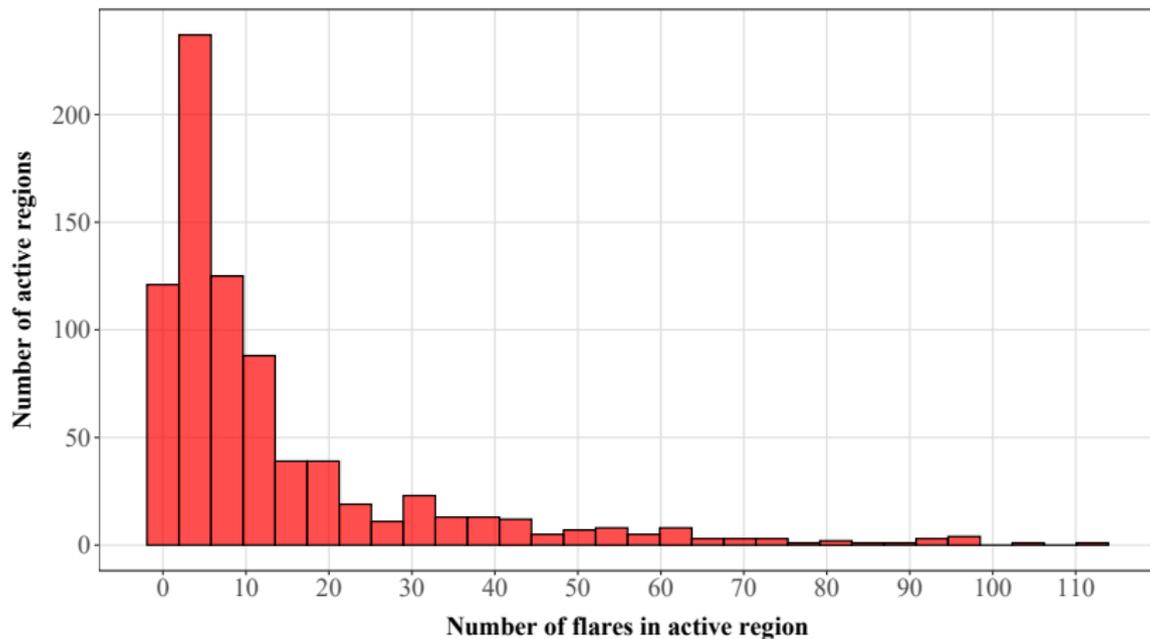
Homogeneous Results w/X-ray Class

The previous results treat all solar flares alike, however we can further test the dependency structure that occurs between x-ray classes.

	Weak Flares (A/B/C)	Strong Flares (M/X)
Weak Flares (A/B/C)	Hypotheses for B/C flares produce significant results at 0.05 level until ~3 days at which flares act as independent events	All hypotheses for M/X vs. C flares produce significant results at 0.05 level
Strong Flares (M/X)		All hypotheses for M vs X flares produce significant results at 0.05 level

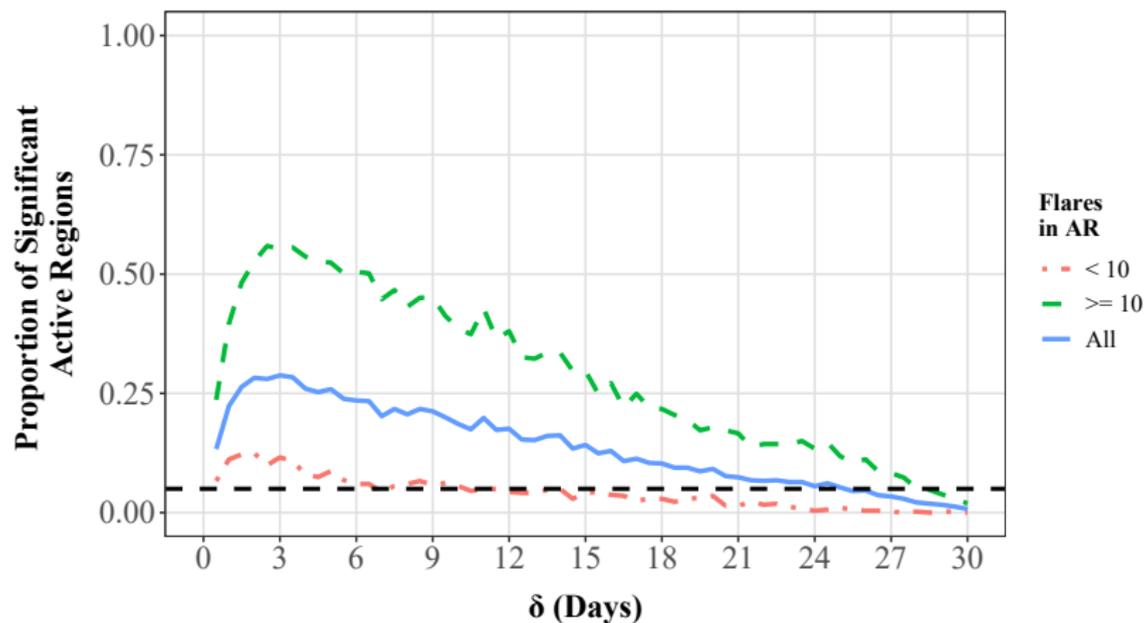
Heterogeneous Results

Histogram of Number of Flares within each AR



Heterogeneous Results

Proportion of Significant Active Regions
by Number of Flares at 0.05 level



Summary

In summary;

- Solar flares are highly dependent events
- In both 'quiet' and 'active' ARs we see that ~ 3 days is when we see the largest dependency
- Flare dependency is not monotonic in the time interval considered
- For weak flares, after 3 days, is when weak flares appear to act as independent events

Thank you for having me!