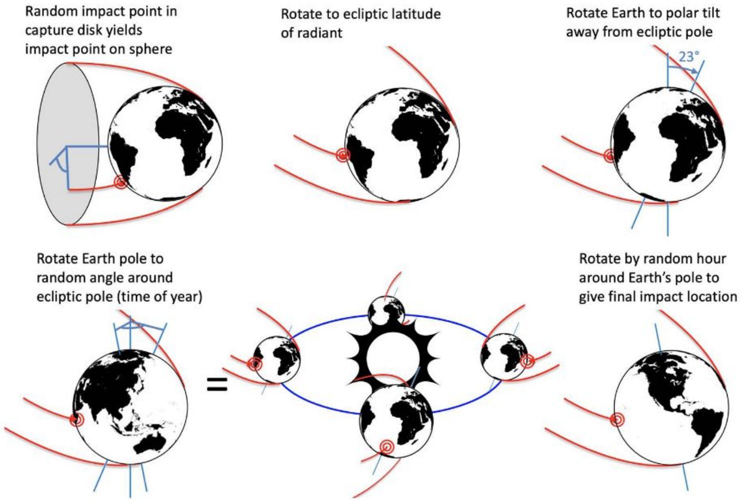
Latitudinal Variation of Bolide Flux as Detected by GOES GLM

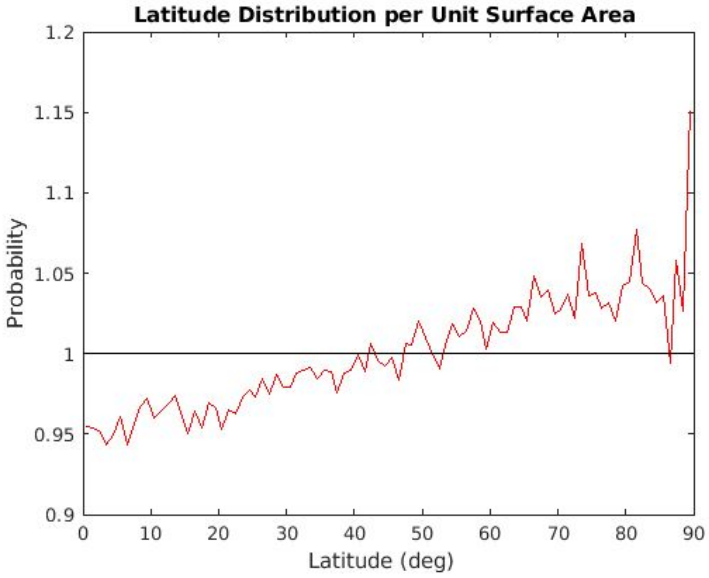
Anthony Ozerov

Mentor: Jeffrey C. Smith

Goal: estimate how bolides impact the Earth across latitudes

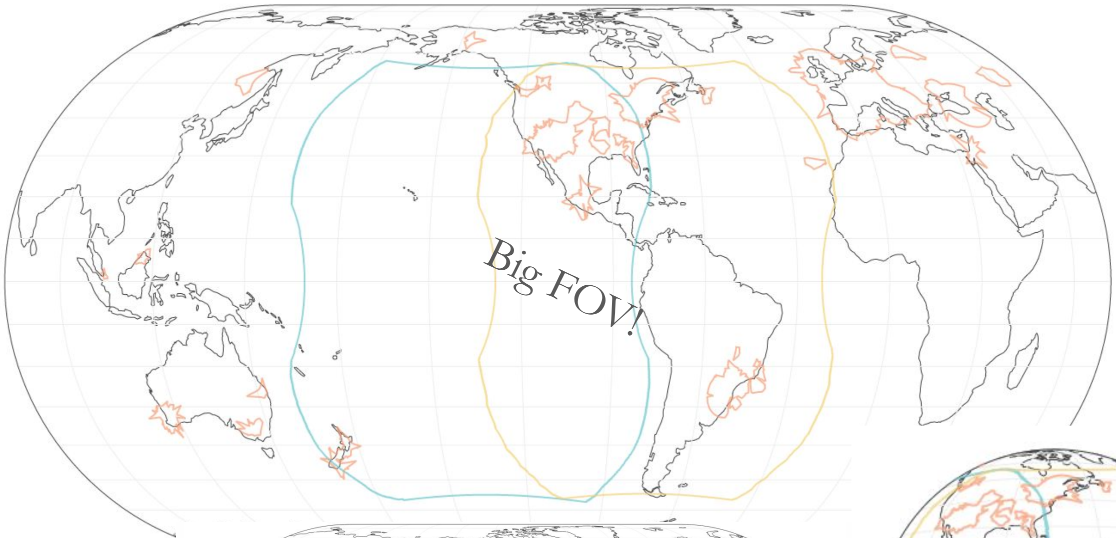
Application: validate theoretical calculations based on NEO population models

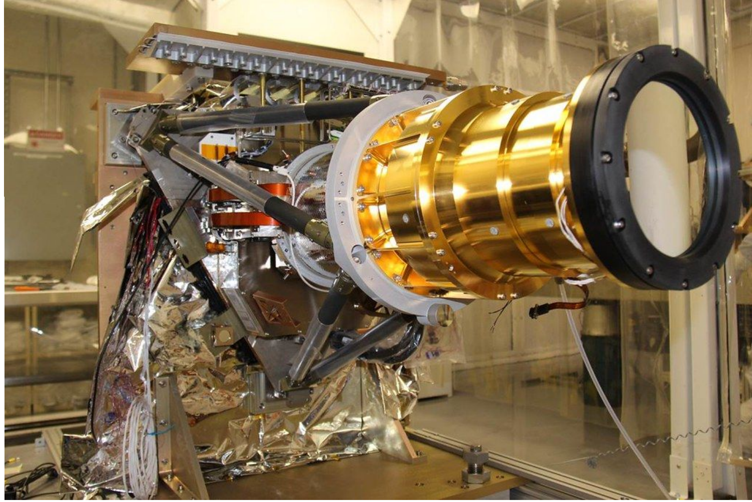


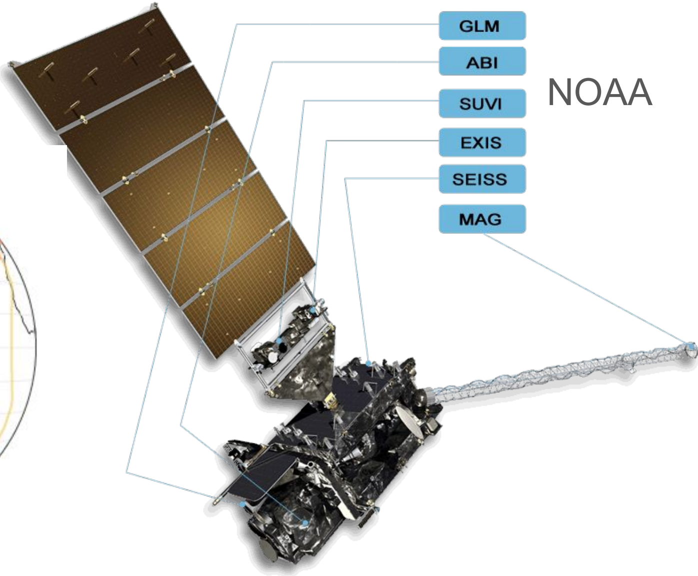


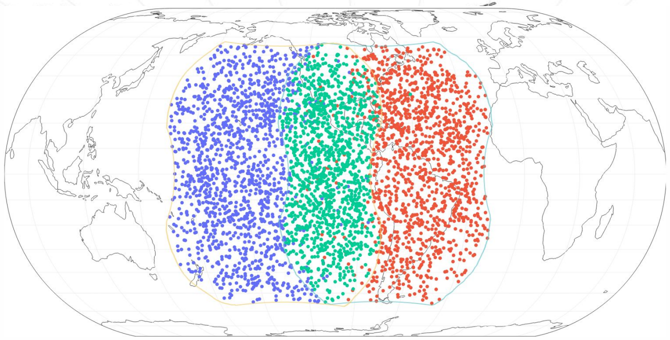
Robertson et. al, 2020

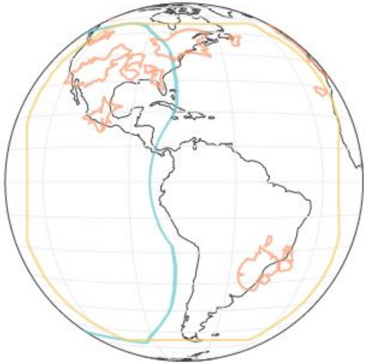
Geostationary Lightning Mapper (GLM)





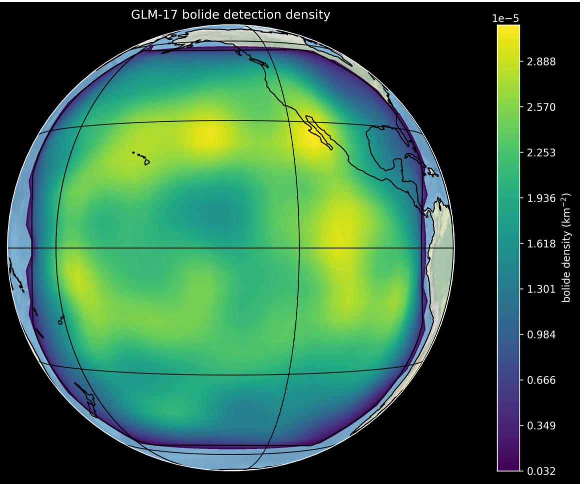


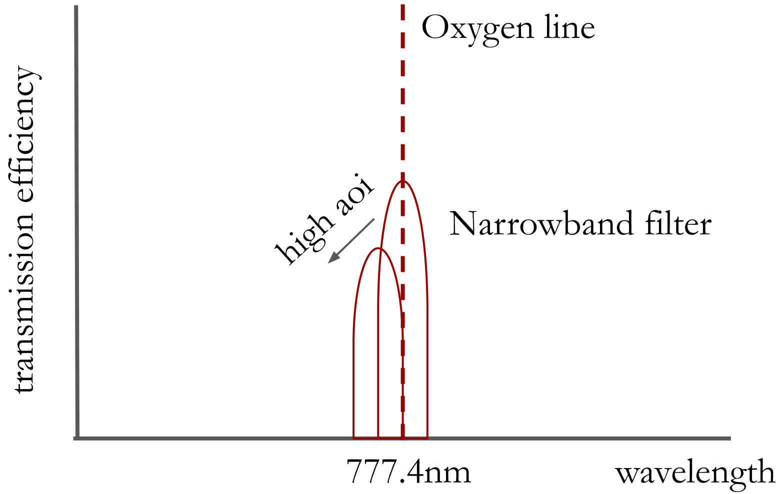


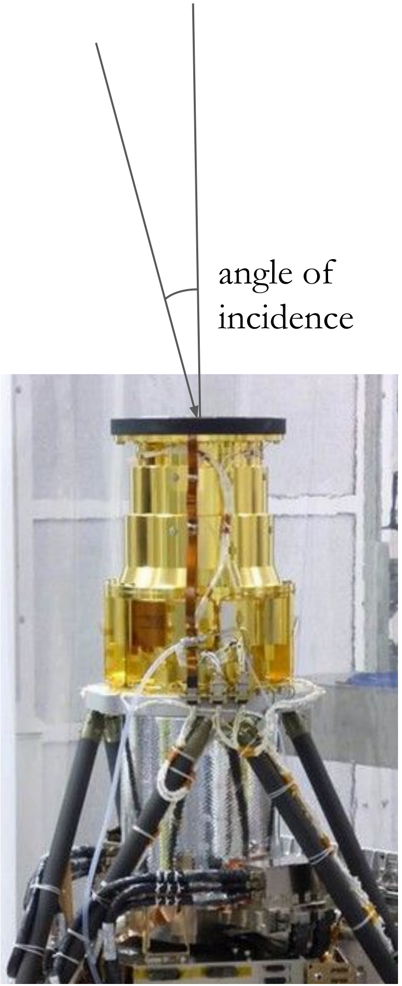


GLM bolide detection problems & biases

- Non-global FOV
- Angle of incidence of light into sensor
- Data show that more massive and faster bolides (→brighter) are easier to detect
- Possible other biases???







NOAA

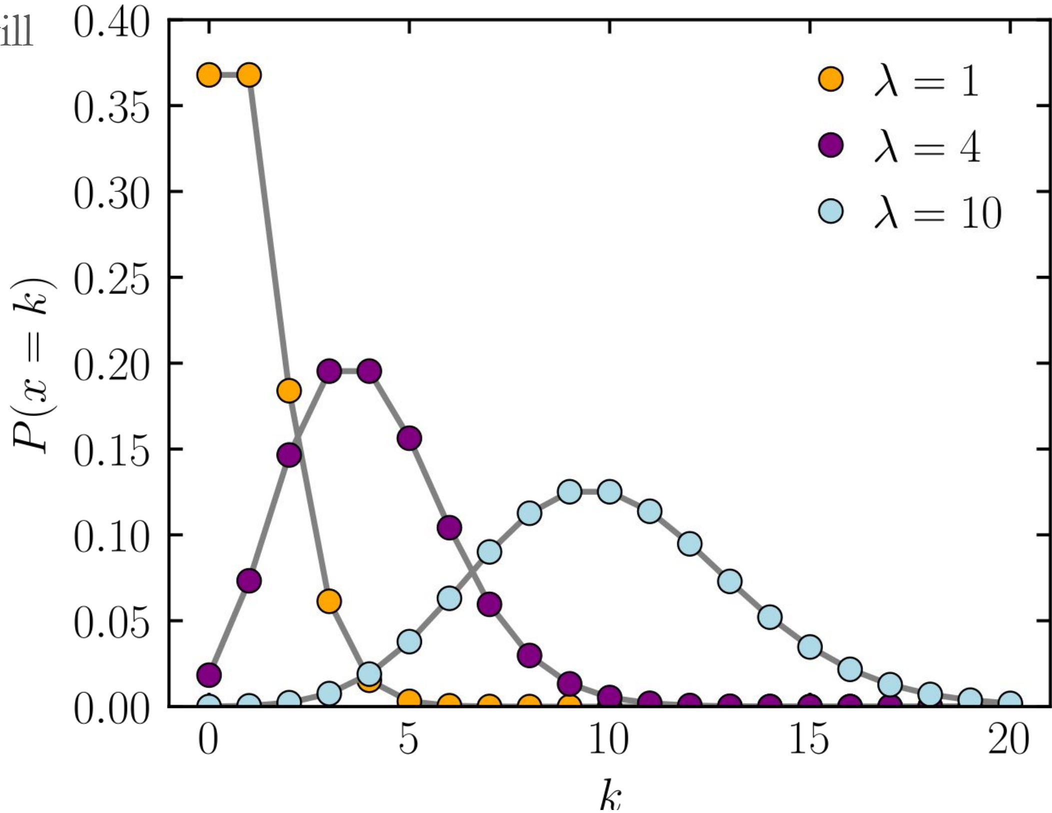
Modeling rates: Poisson Distribution

If I run a bagel store, how many people will arrive between 11:00 and 12:00?

If am an area on the Earth, how many bolides will be detected in me between 2019 and 2022?

Notation	$\mathrm{Pois}(\lambda)$
Parameters	$\lambda \in (0, \infty)$ (rate)
Support	$k \in \mathbb{N}_0$ (Natural numbers starting from 0)
PMF	$\frac{\lambda^k e^{-\lambda}}{k!}$

https://en.wikipedia.org/wiki/Poisson_distribution



The Model

Observed number of bolides in area A
In period of time T

Inhomogeneous rate function

Latitude

$$y(A,T) \sim \text{Poisson}\left(\int_T \int_A \Lambda(d,l,t)\ dd\ dl\ dt\right)$$

Distance from nadir

Time

$$\Lambda(d,l,t) = b(d) \sum_{s \in S(t)} \lambda_s(l)$$

bias due to angle
of incidence

Sum of rates due to different
sources (background, showers)

Regression on
distance from
nadir

$$b(d) = \exp(\alpha_0 + \alpha_1 d + \alpha_2 d^2 + \alpha_3 d^3)$$

Regression on
latitude

$$\lambda_s(l) = \exp(\beta_{s,0} + \beta_{s,1} l + \beta_{s,2} l^2 + \beta_{s,3} |l^3|)$$

The Model

Observed number of bolides in area A
In period of time T

Inhomogeneous rate function

Latitude

$$y(A,T) \sim \text{Poisson}\left(\int_T \int_A \Lambda(d,l,t)\ dd\ dl\ dt\right)$$

Distance from nadir

Time

$$\Lambda(d,l,t) = b(d) \sum_{s \in S(t)} \lambda_s(l)$$

bias due to angle
of incidence

Sum of rates due to different
sources (background, showers)

Nonparametric version!

Function of
distance from
nadir

$$b(d) = \exp(f_b(d));\ \ f_b(x) \sim GP(m(x), k(x,x'))$$

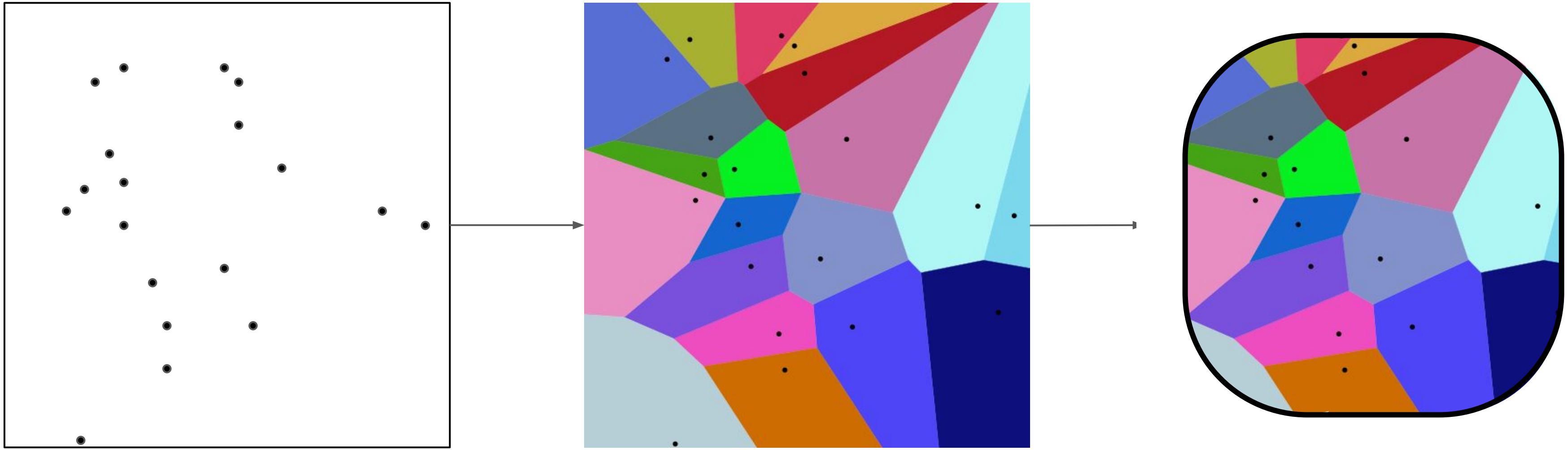
Function of
latitude

$$\lambda_s(l) = \exp(f_s(l));\ \ f_s(x) \sim GP(m(x), k(x,x'))$$

Scatter data → discretized count data

1. Split bolides according to satellite

2. For a satellite, randomly split the GLM FOV into small polygons

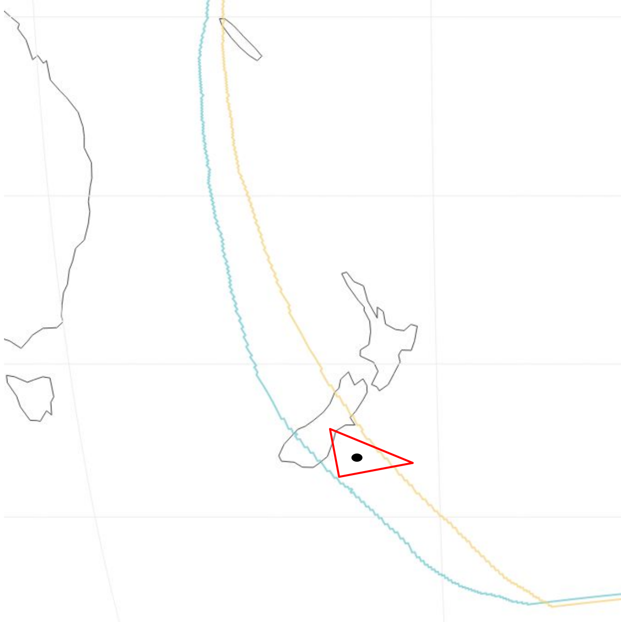


Uniformly random points

Voronoi diagram
to get polygons

Clip to FOV

Scatter data → discretized count data



3. Split bolides into different showers and the background rate based on time.

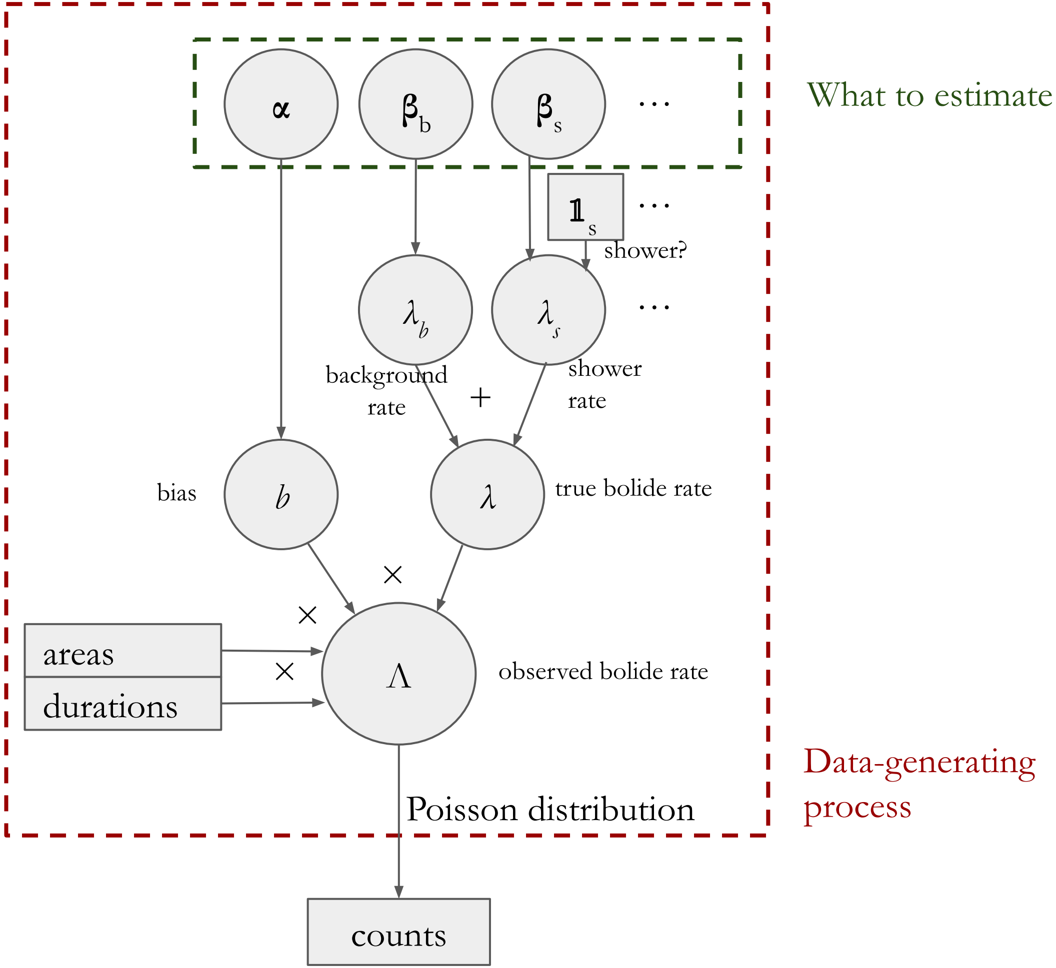
4. Collect polygon data

- **Count**: number of bolides within polygon
- **Area**: area of polygon
- **Duration**: Normalized GLM observing time
- **Latitude**: Latitude of centroid
- **Nadir distance**: Centroid's distance from satellite's nadir:
- **Source:** what shower this data is for

5. Re-combine data for all showers and both satellites

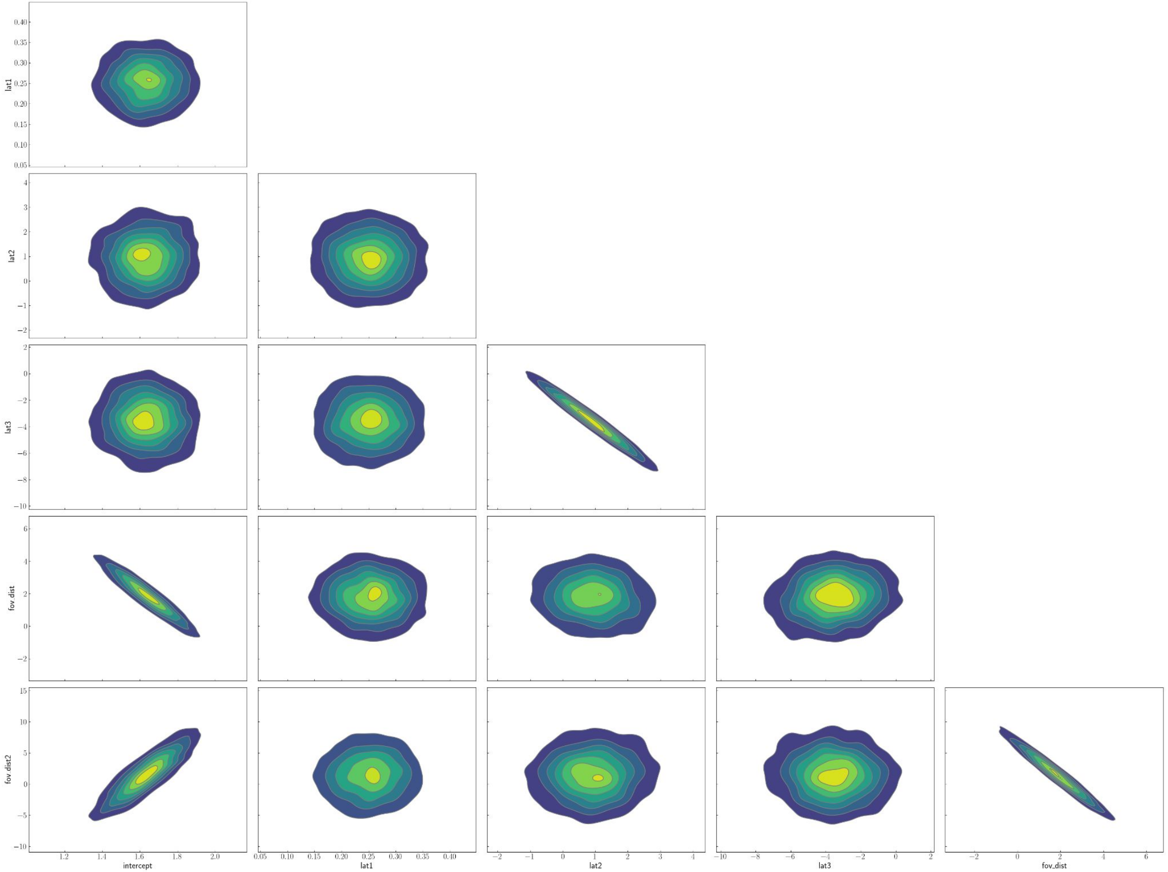
count	latitude	nadir distance	area	duration	leonids?
5	37.2°	5000km	5	1	0
…	…	…	…	…	…

Overview

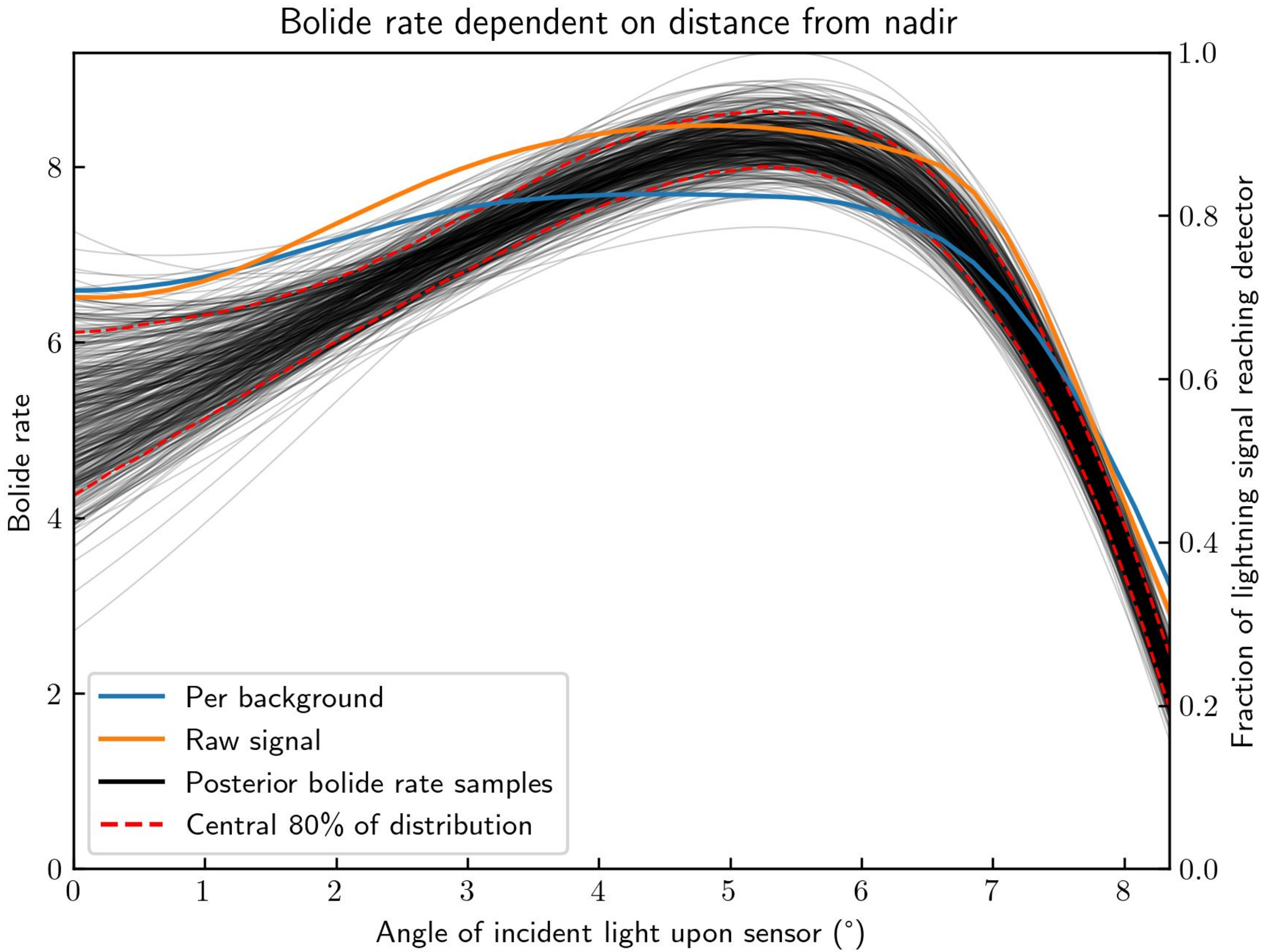


α
β_b
β_s
…
What to estimate
$\mathbb{1}_s$
shower?
λ_b
λ_s
background rate
+
shower rate
bias
b
λ
true bolide rate
×
areas
durations
Λ
observed bolide rate
Poisson distribution
Data-generating process
counts

Markov chain Monte-Carlo to obtain posteriors

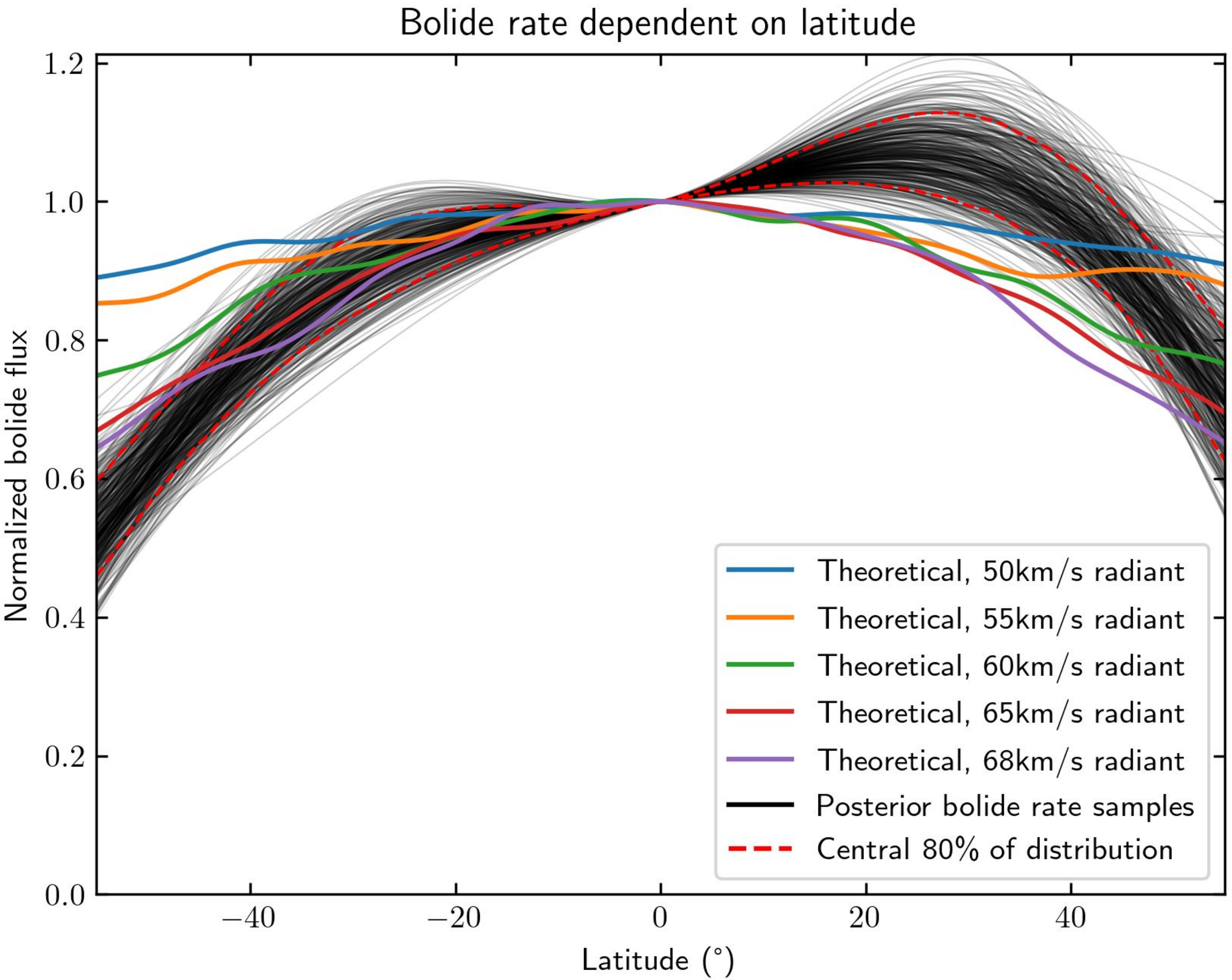


b



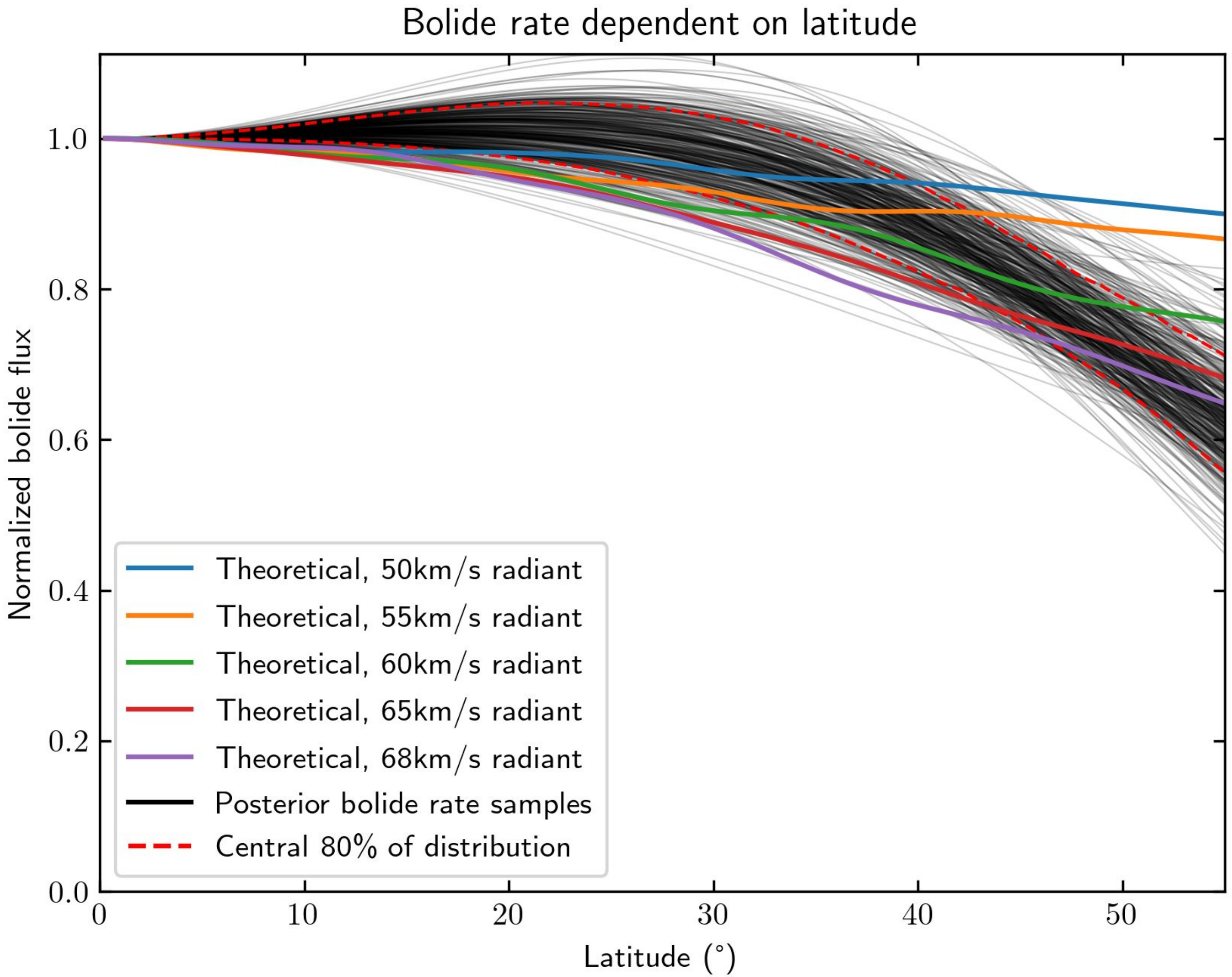
Bolide rate dependent on distance from nadir
Bolide rate
Fraction of lightning signal reaching detector
Angle of incident light upon sensor (°)
0
2
4
6
8
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
Per background
Raw signal
Posterior bolide rate samples
Central 80% of distribution

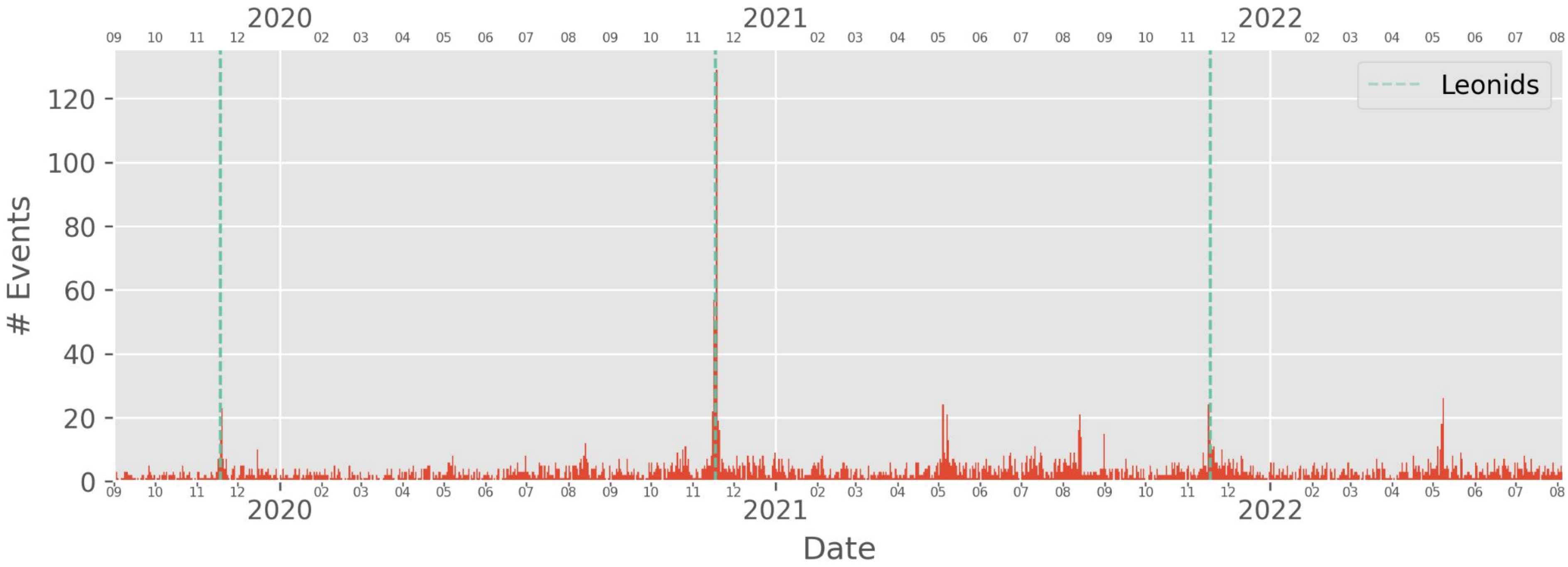
λ_b



Bolide rate dependent on latitude
Normalized bolide flux
Latitude (°)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−40
−20
0
20
40
Theoretical, 50km/s radiant
Theoretical, 55km/s radiant
Theoretical, 60km/s radiant
Theoretical, 65km/s radiant
Theoretical, 68km/s radiant
Posterior bolide rate samples
Central 80% of distribution

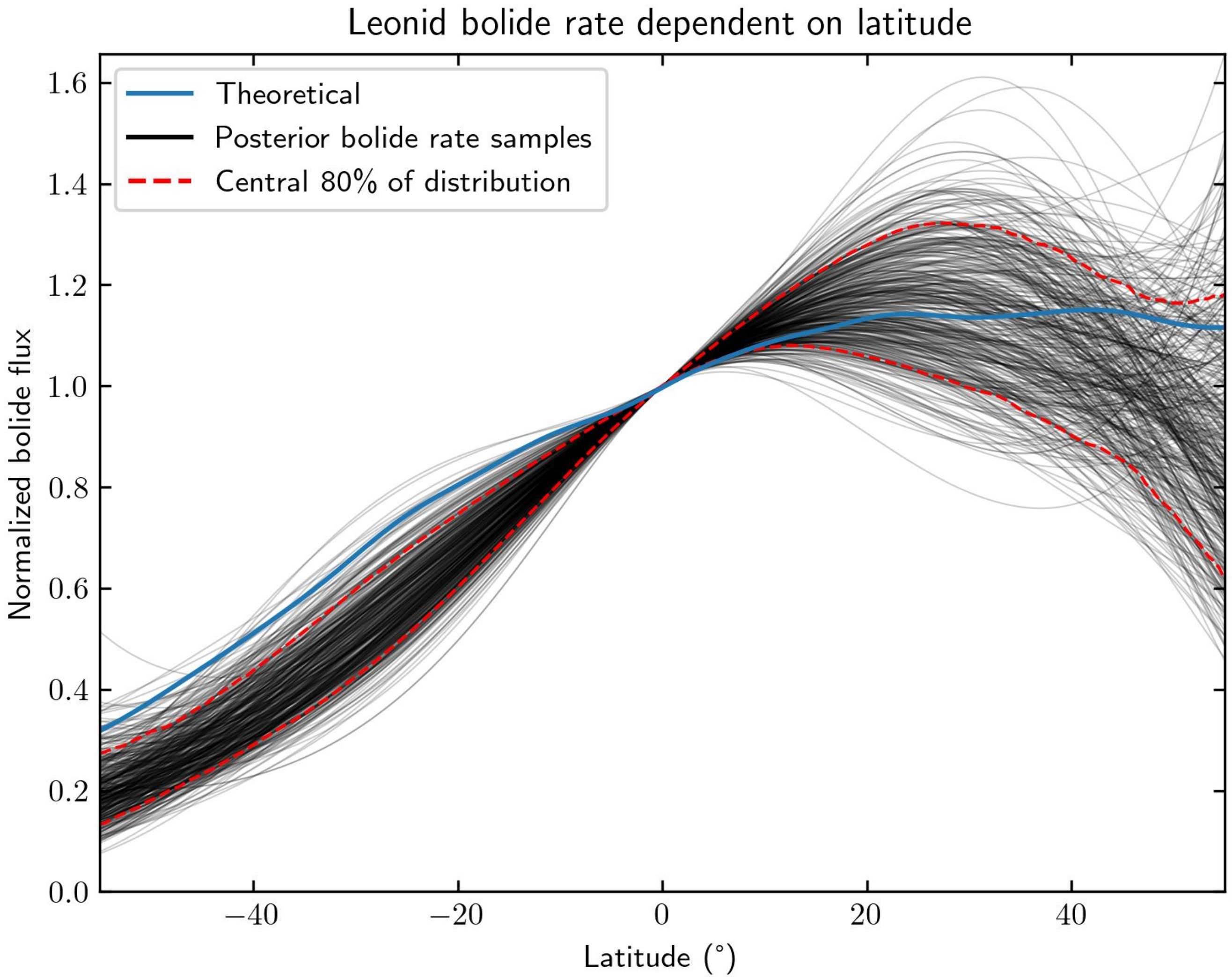
λ_b


Bolide rate dependent on latitude
Normalized bolide flux
Latitude (°)
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
Theoretical, 50km/s radiant
Theoretical, 55km/s radiant
Theoretical, 60km/s radiant
Theoretical, 65km/s radiant
Theoretical, 68km/s radiant
Posterior bolide rate samples
Central 80% of distribution



2020
2021
2022
09
10
11
12
02
03
04
05
06
07
08
Leonids
120
100
80
60
40
20
0
Events
Date

λ_s



Leonid bolide rate dependent on latitude
Theoretical
Posterior bolide rate samples
Central 80% of distribution
Normalized bolide flux
Latitude (°)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
−40
−20
0
20
40

Conclusion

- Successfully estimated GLM detection bias due to angle of incidence
- Distribution across latitudes consistent with GLM being biased towards fast objects
- Can separate out meteor showers from background rate

Further study:

- Study other, less intense meteor showers
- Nonparametrics and model comparison
- De-biasing according to velocity
- Computing and studying velocities, trajectories, and orbits in the stereo region

Python package

bolides

A package to analyze bolide data in Python.

pypi v0.3 | docs passing | launch binder

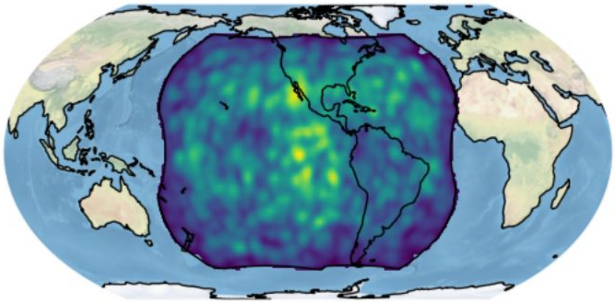
bolides.readthedocs.io

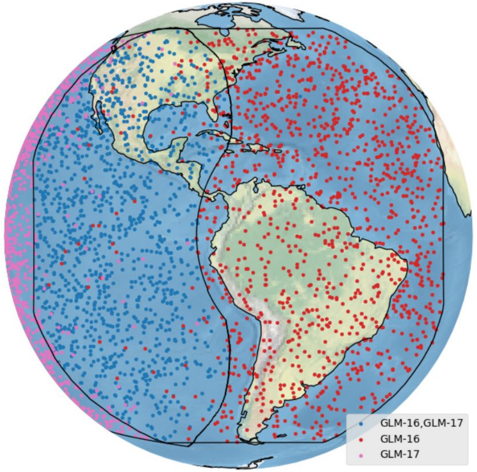
```
bdf = BolideDataFrame(source='usg')
```

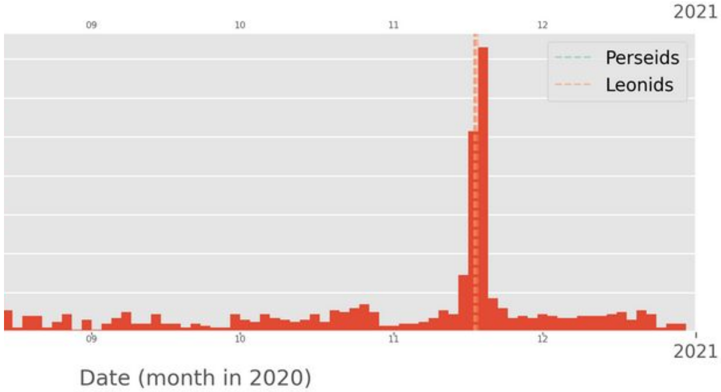
```
[7]: bdf
```

[7]: GLM bolide detections from neo-bolide.ndc.nasa.gov, developed and operated by NASA's Asteroid Threa
Assessment Project thanks to funding from NASA's Planetary Defense Coordination Office.

	datetime	longitude	latitude	source	detectedBy	confidenceRating	lightcurveStructure	energy_g
0	2022-07-18 21:30:03	-96.6	-18.5	website	GLM-16,GLM-17	medium	very good	2.284910e-
1	2022-07-18 15:22:59	-111.0	28.0	website	GLM-16,GLM-17	medium	good	3.084814e-
2	2022-07-18 13:04:02	-40.8	4.2	website	GLM-16	low	minimal	3.184802e-







Interactive Bolide Data Visualizer

bolides.seti.org

Select a data source

USG data at cneos.jpl.nasa.gov/fireballs/

GLM data at neo-bolide.ndc.nasa.gov/

Global Meteor Network data at globalmeteornetwork.org/data/

Meteor shower data at www.ta3.sk/IAUC22DB/MDC2007/

USG data with computed orbits

Date filters: start date yyyy-mm-dd end date yyyy-mm-dd

Meteor shower filter: Select meteor shower(s)

Field-of-view options:

☐ goes ☐ goes-e ☐ goes-w ☐ goes-w-ni ☐ goes-w-i ☐ fy4a ☐ fy4a-n ☐ fy4a-s ☐ gmn-25km ☐ gmn-70km ☐ gmn-100km

☐ Filter by FOV ☐ Intersection

Sensor observation filters: ☐ glm16 ☐ glm17 ☐ Intersection

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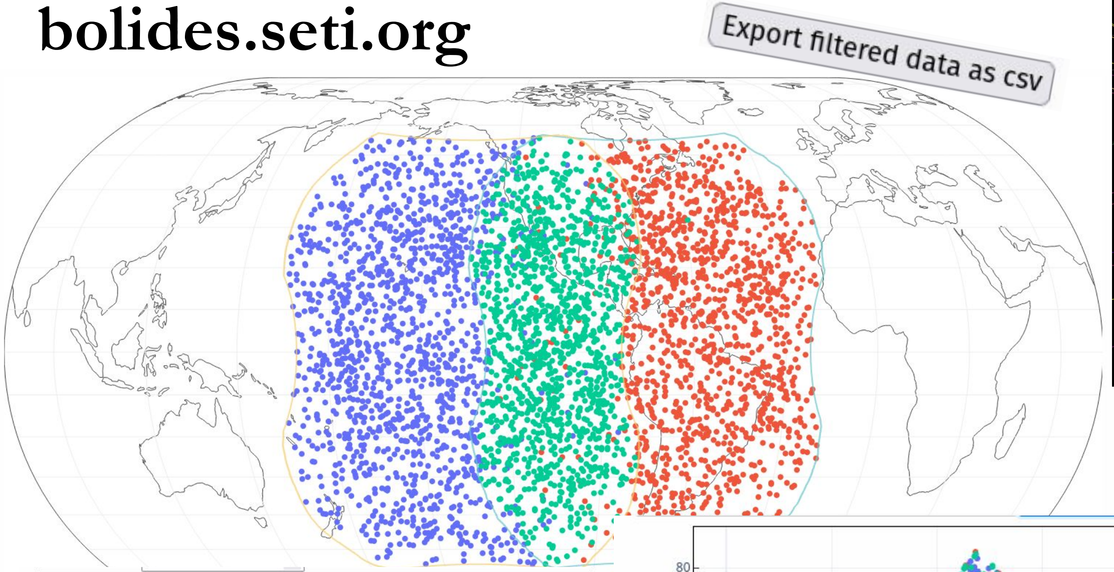

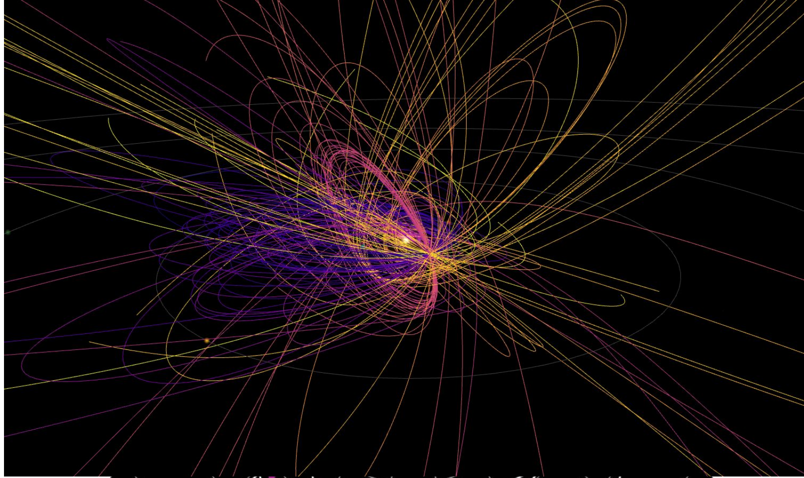

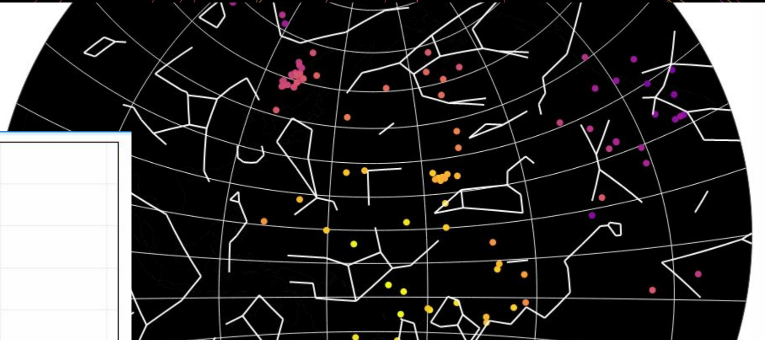

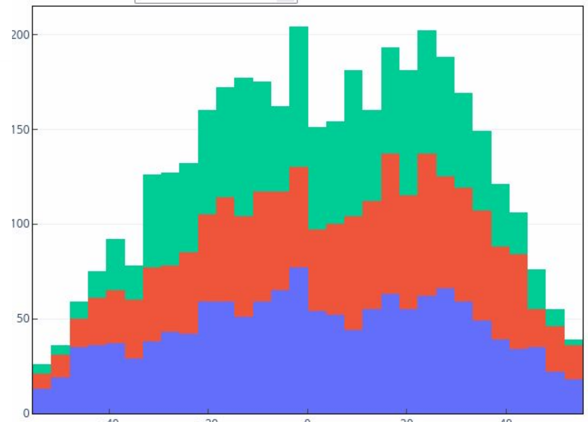

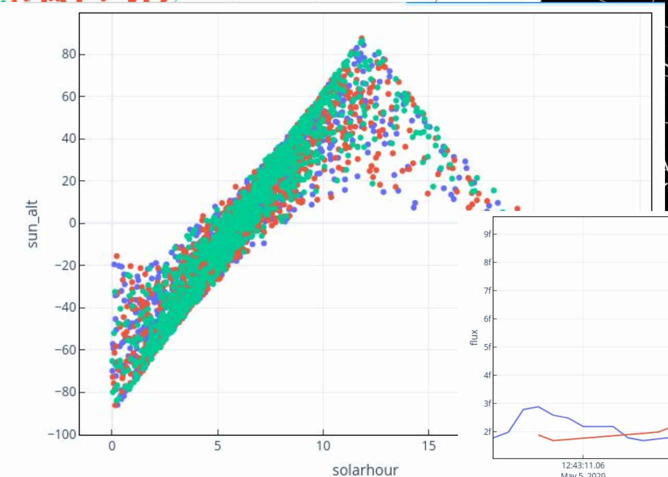

Acknowledgments

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Darrel Robertson: Impact simulation code, helpful discussion
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- Jessie Dotson
- Robert Morris
- Randy Longenbaugh
- Tasan Smith-Gandy
- Nina McCurdy

Katrina Virts: FOV data

Developers of open-source software, especially:

- Python and the scientific Python stack
- Lightkurve, Astropy
- PyMC
- Linux, Ubuntu, Nginx, Flask, Plotly, Spacekit

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$$\int_A \Lambda(d, l, t)\; dd\; dl \approx a_A \Lambda(d_A, l_A, t)$$

$$\int_T a_A \cdot \Lambda(d_A, l_A, t) dt = \mu(T) \Lambda(d_A, l_A, t_0),$$