MODELLING AFTERSHOCK SEQUENCES IN NET-VISA

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Motivation

- Natural seismic events when observed over a long period of time exhibit distinct clustering patterns
- After a large seismic event a short-lived clustering is observed around the location of the large event
- Building a model of this clustering helps to better identify natural seismic events, and ultimately improve accuracy on man-made seismic events
- The current work aims to identify the factors which best predict the location of future seismic events

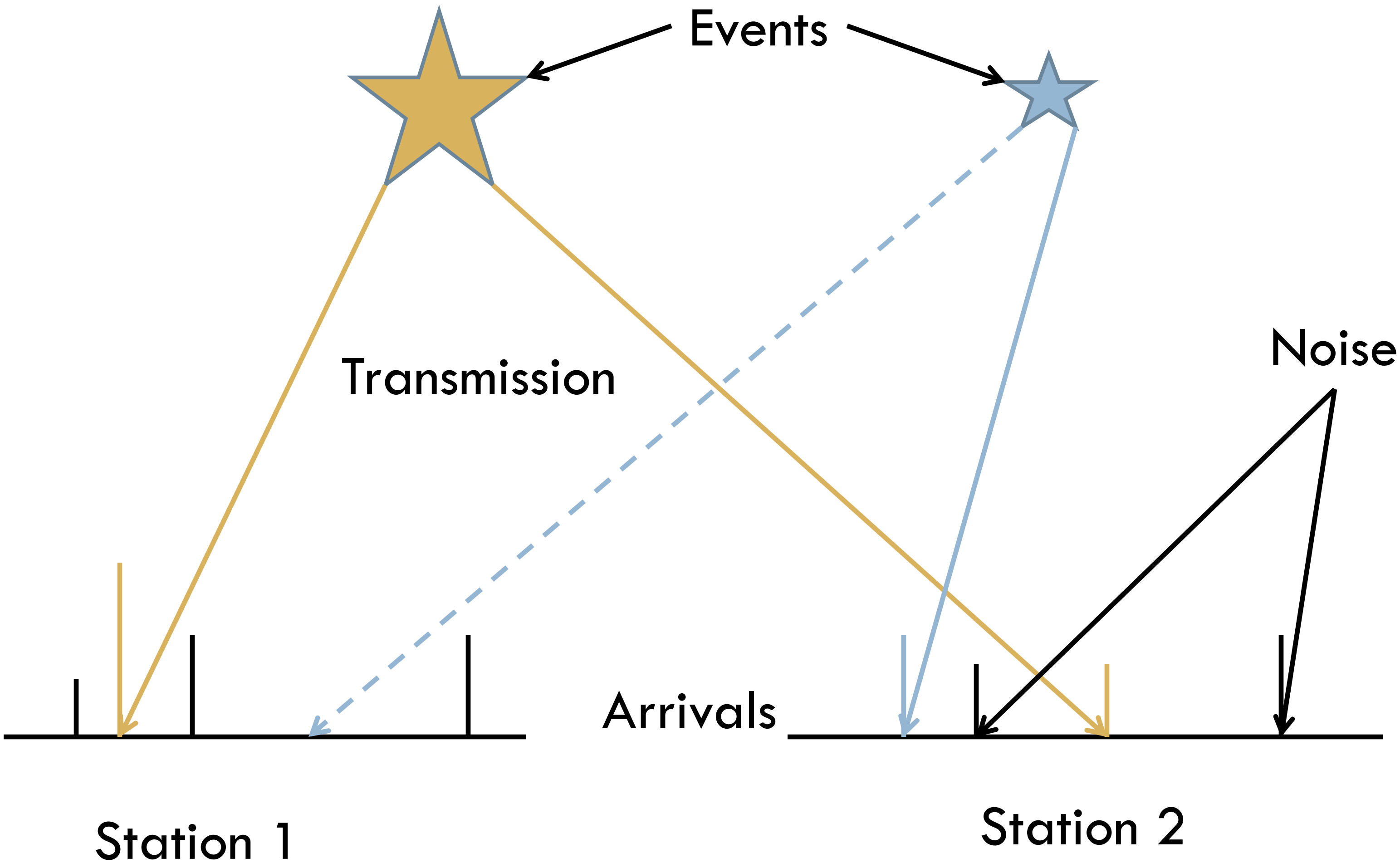
Outline

- Motivation
- NET-VISA overview
- Kernel-based event rate estimation
- Time decaying model
- Magnitude sensitive model
- Conclusion

NET-VISA overview

- Probabilistic generative model of
  - Seismic Events
    - Location
    - Magnitude
  - Transmission of seismic waves
    - Amplitude decay
    - Velocity
  - Noise
  - Observed waveform parameters at the seismic stations
- Calibrated on historical data
- Infers *maximum a-posteriori* bulletin of all events

Generative Model



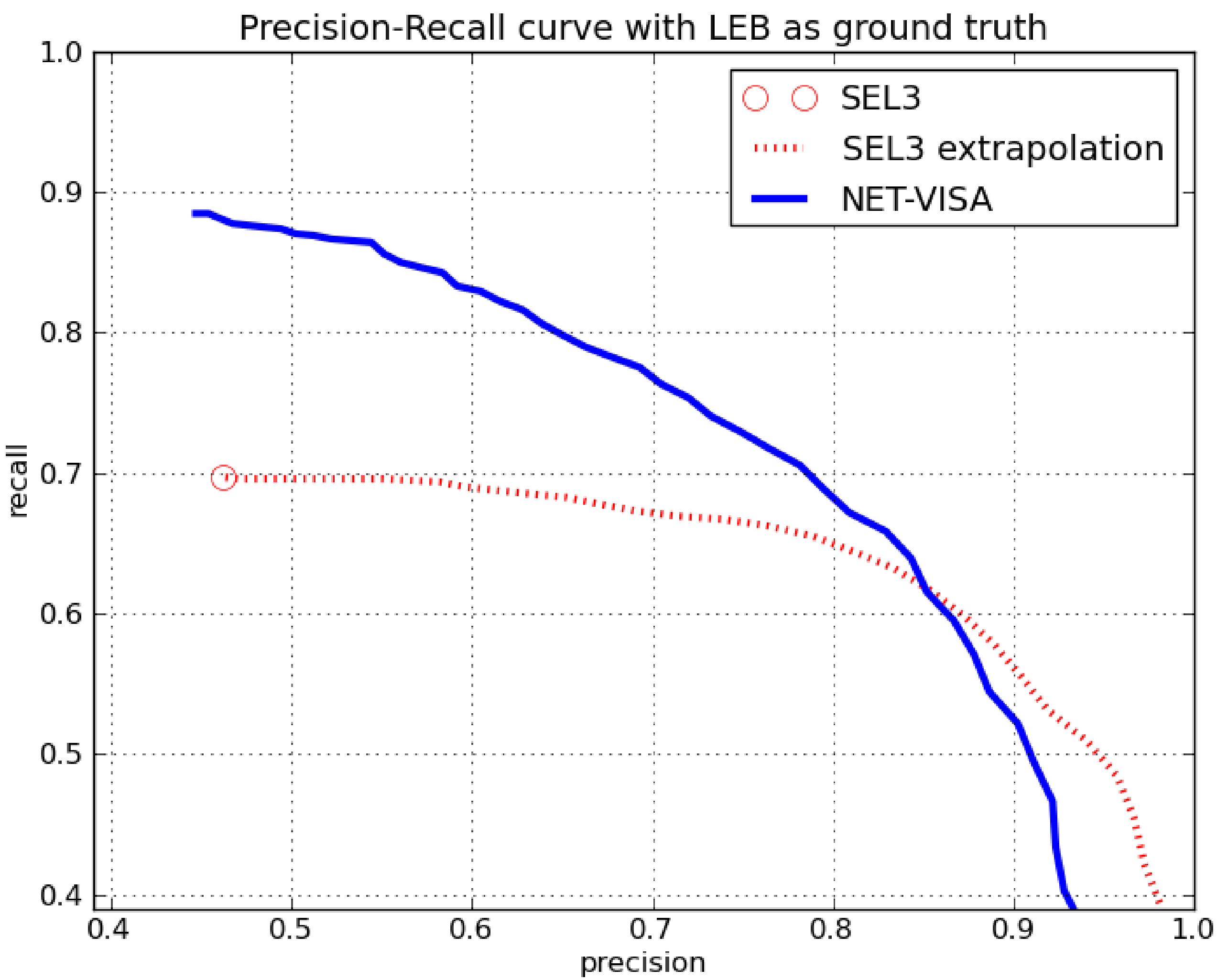
Inference

- Number of Events
- Event
  - Location (longitude, latitude)
  - Depth
  - m_b
  - Time
- Is Detected(event, station, phase) -> [true or false]
- Number of false detections per station
- Detection
  - Arrival Time
  - Arrival Azimuth
  - Arrival Slowness
  - Arrival Phase
  - Arrival Amplitude
  - Source -> [event or null]
  - True Phase -> [phase or null]

Inference Overview

- Continuously extend hypothesis by incorporating new detections
- Greedy moves improve the probability
  - Birth
  - Re-associate
  - Relocate
  - Death

NET-VISA Precision – Recall



Recall & Error by m_b

m_b	#events	Recall		Error (km)	
		SEL3	NET-VISA	SEL3	NET-VISA
0 – 2	74	64.9	89.2	101	106
2 – 3	36	50.0	86.1	186	140
3 – 4	558	66.5	86.2	104	121
> 4	164	86.6	93.9	70	77
All	**832**	**69.7**	**88.1**	**99**	**112**

Recall & Error by Azimuth Gap

Gap	#events	Recall		Error (km)	
		SEL3		SEL3	
			NET-VISA		NET-VISA
0 – 90	72	100.0		28	
			100.0		39
90 – 180	315	88.9		76	
			93.7		75
180 – 270	302	51.0		134	
			84.4		137
270 - 360	143	51.0		176	
			76.9		198
All	**832**	**69.7**		**99**	
			88.1		**112**

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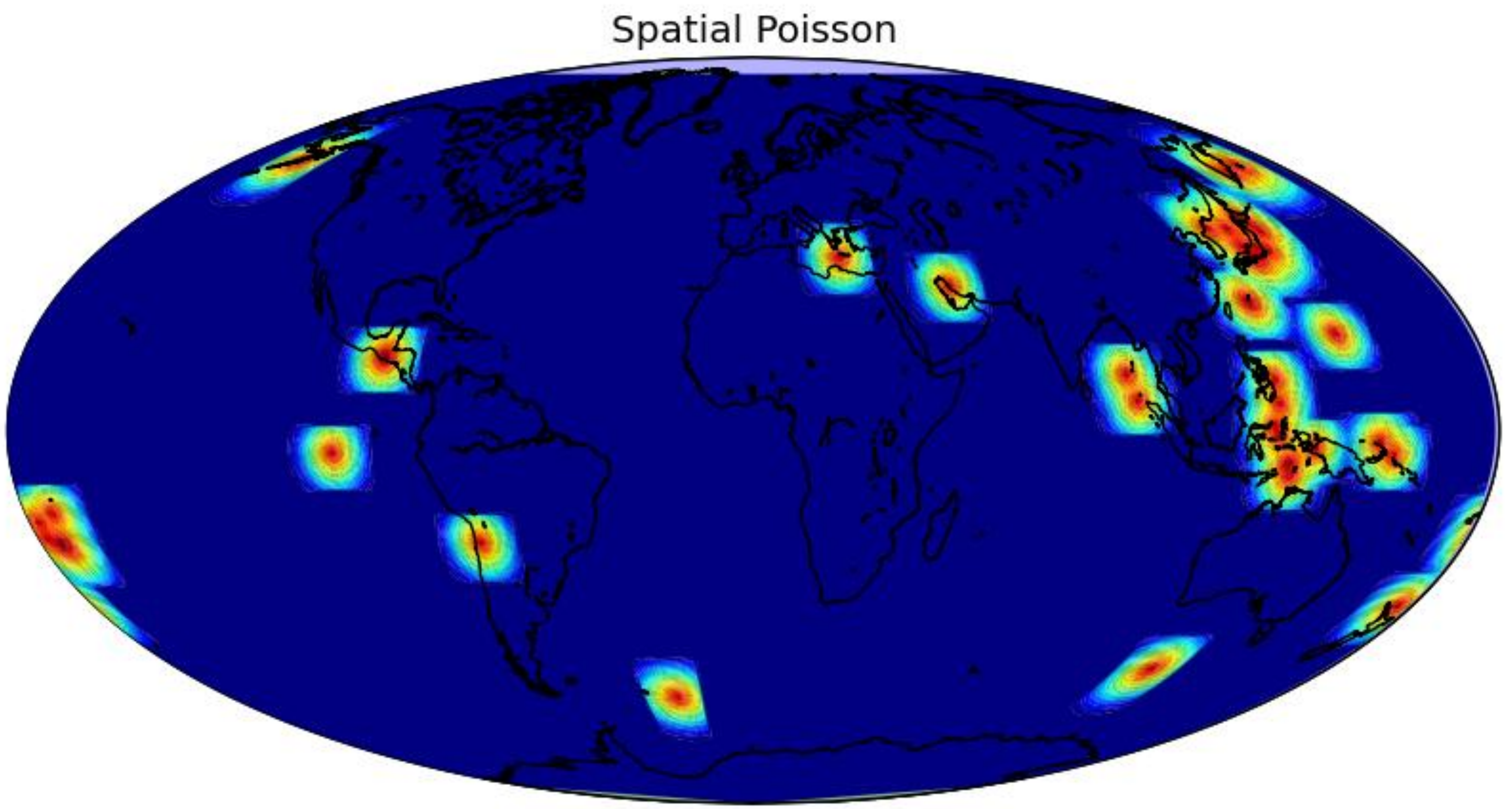
Kernel Rate Estimation

$$\lambda(y) = \frac{1}{T}\sum_{i=1}^{n} K_{b,x_i}(y)$$

- x_i's are the locations of the previous events
- T is the time over which all the previous events occurred

Kernel Rate-based Prior

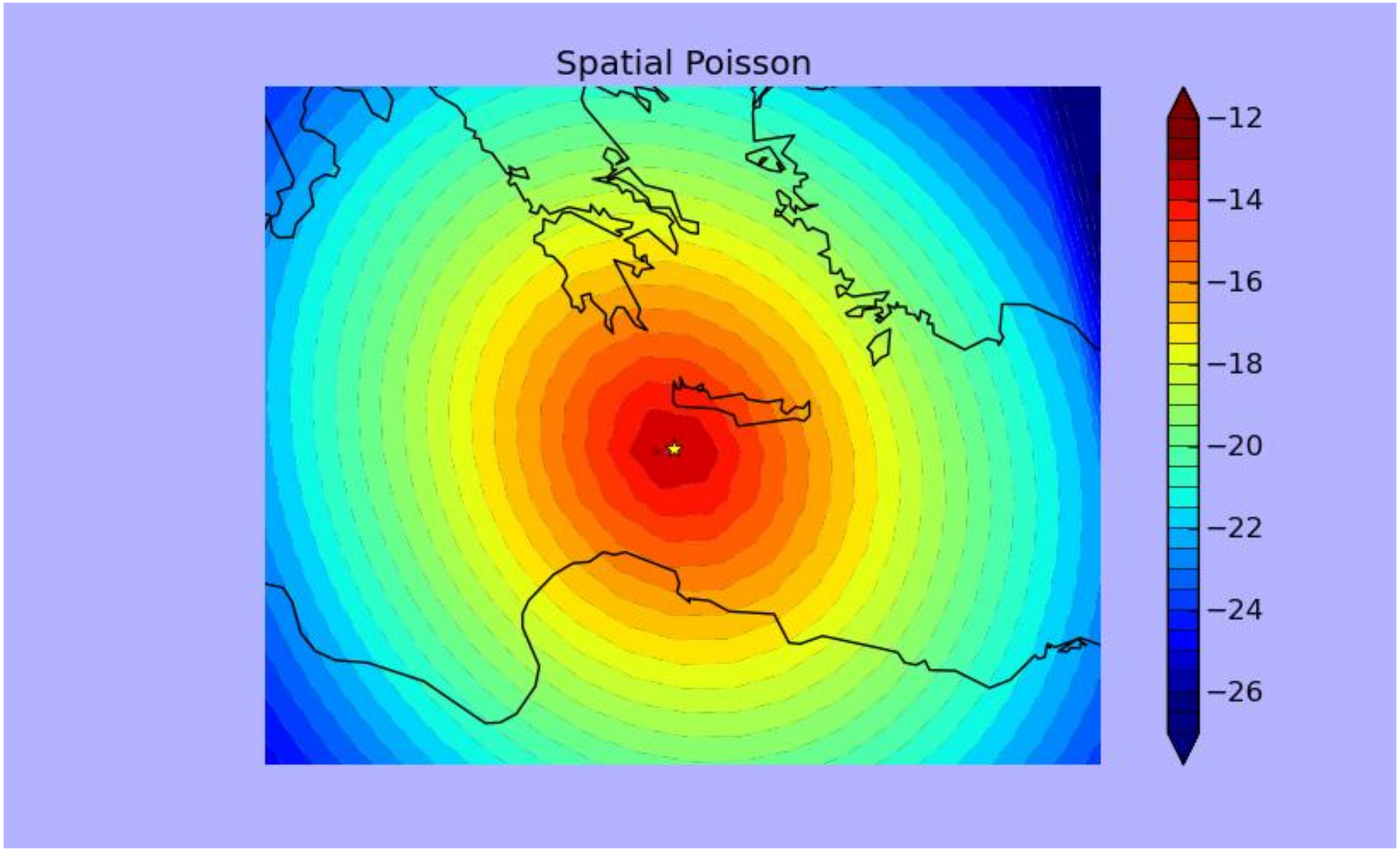


The kernel function

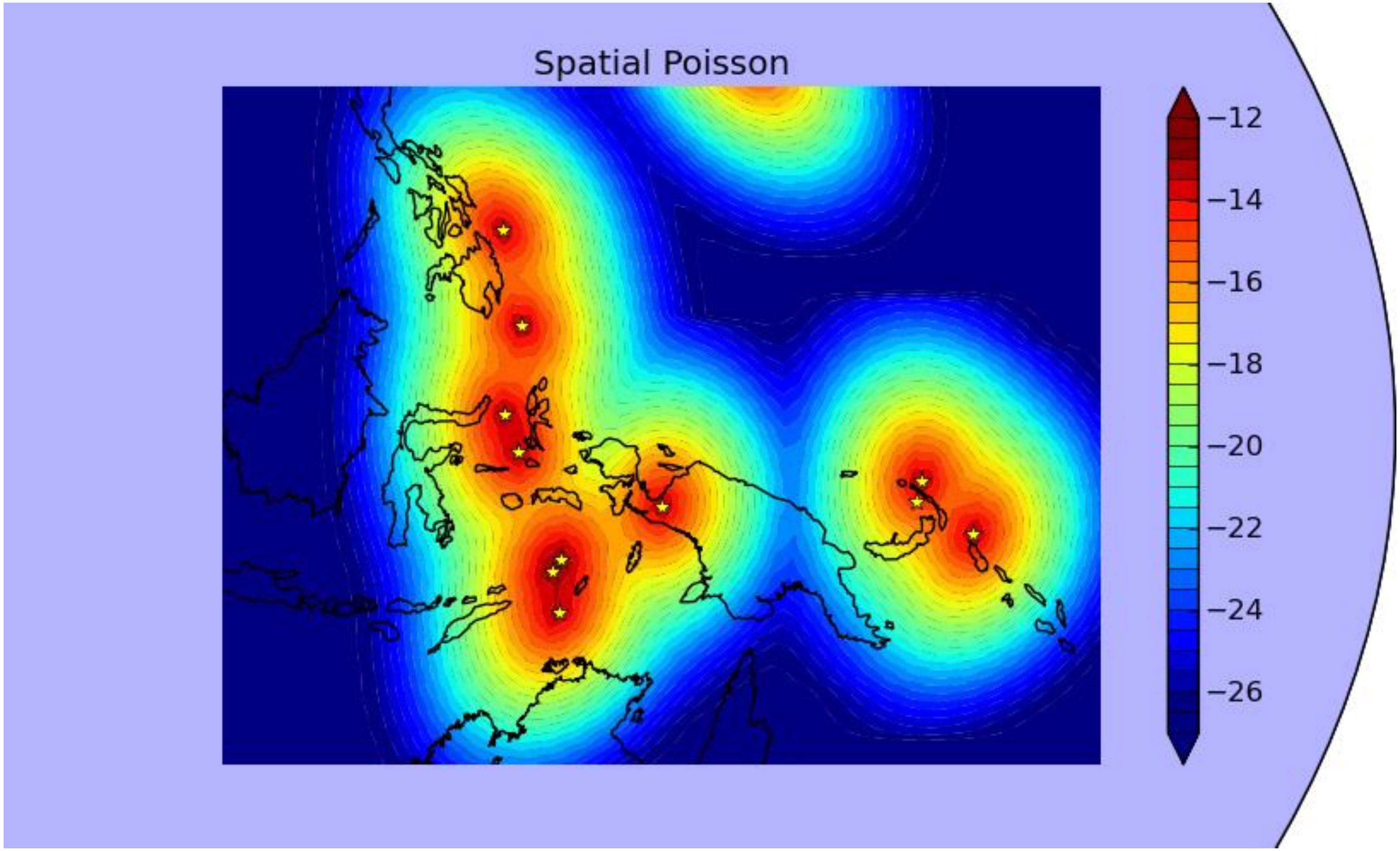
$$K_{b,x}(y) = \frac{1+\frac{1}{b^2}}{2\pi R^2} \frac{\exp(-\frac{\Delta_{xy}}{b})}{1+\exp(-\frac{\pi}{b})}$$

- b is the bandwidth of the kernel
- Δ_{xy} is the great-circle distance between locations x and y
- R is the radius of the earth
- Optimal b learned by cross-validation ~ 80km

The kernel function (log scale)



Sum of kernel functions



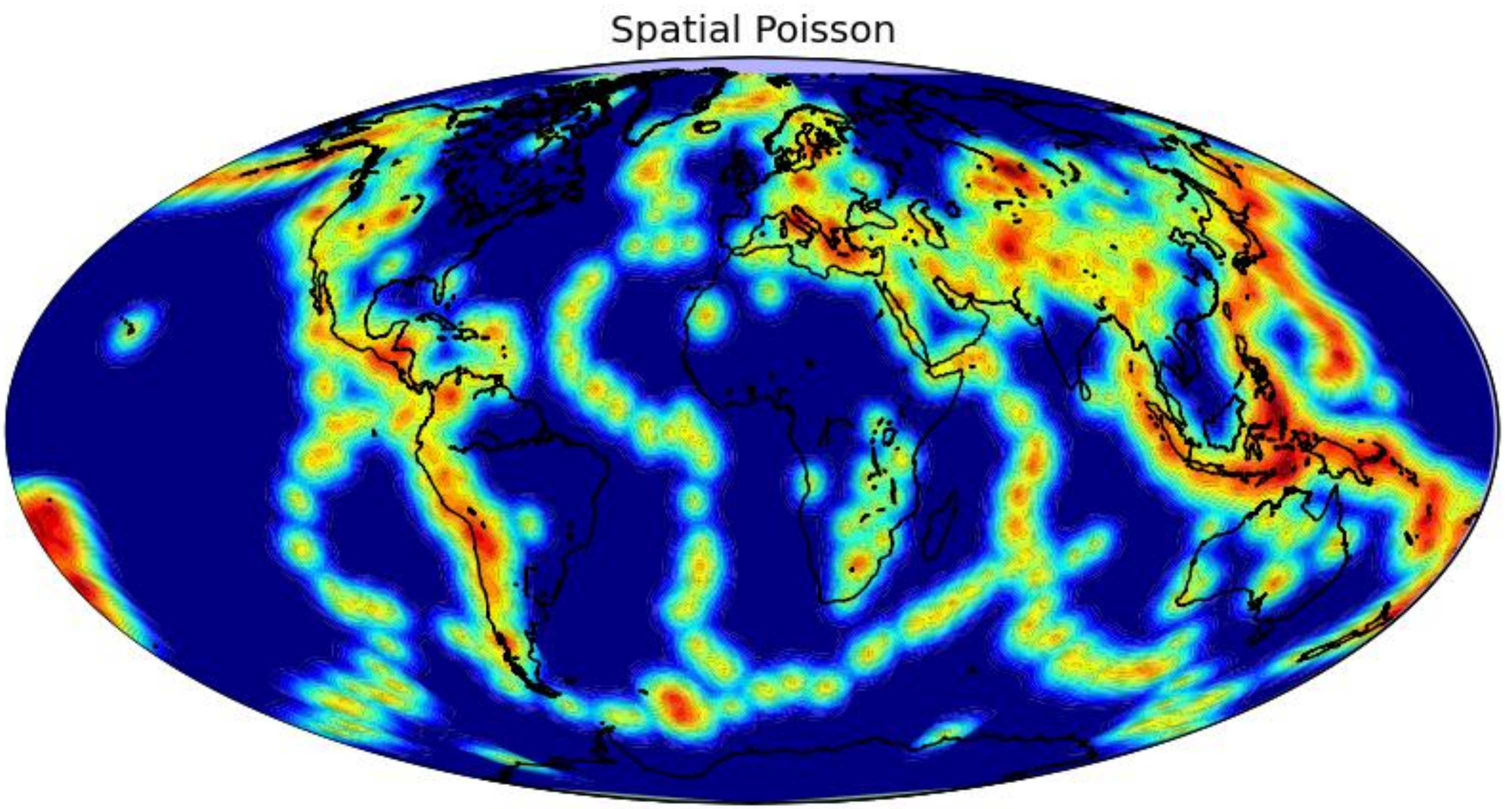
Implementation…

- Poisson rates are computed on a grid and intermediate points are intepolated
- Online update for the Poisson rate

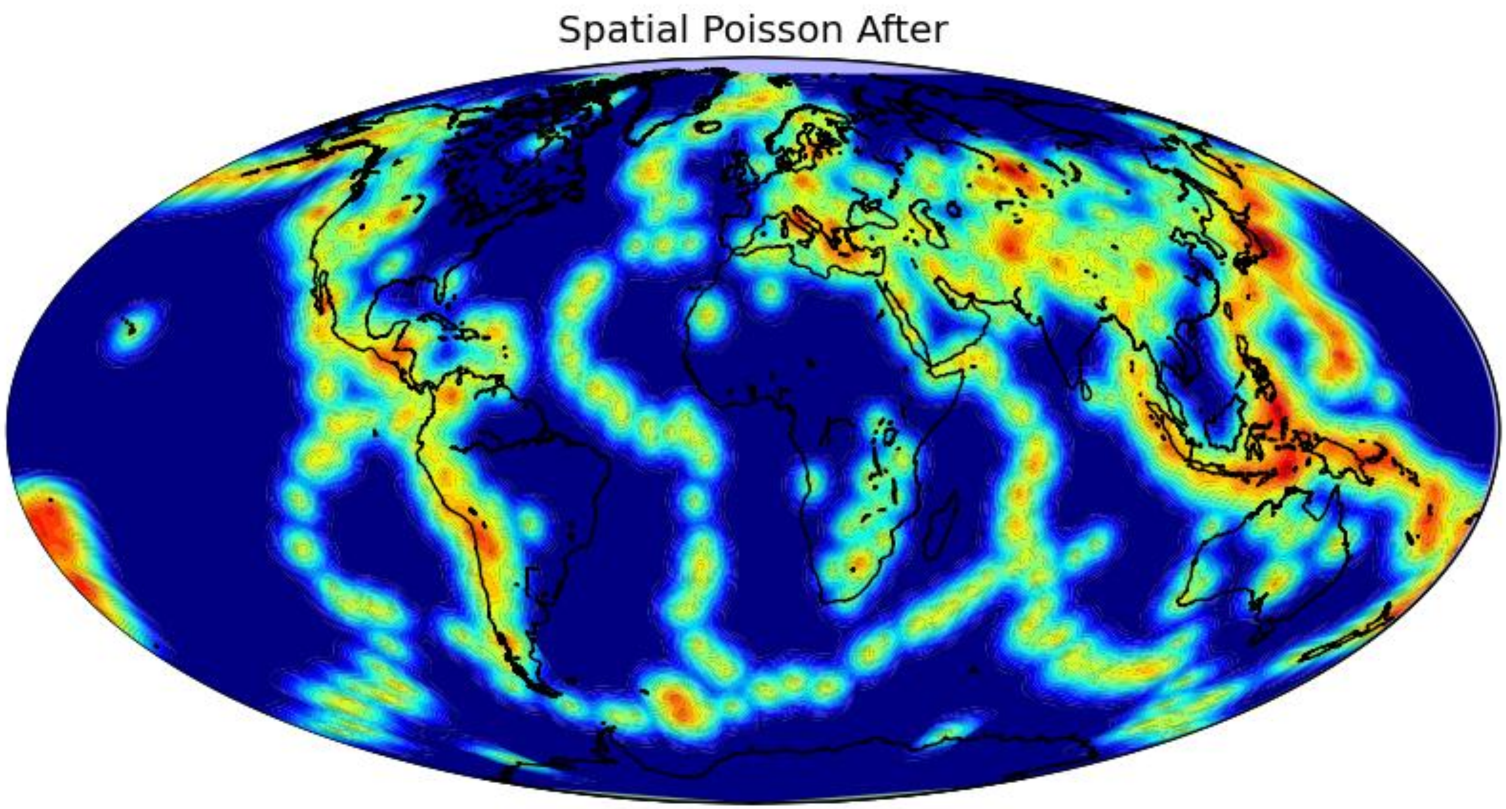
$$\mu_{n+1} = \alpha \mu_n + (1 - \alpha) x_{n+1}$$

$$\alpha = \frac{n}{n+1}$$

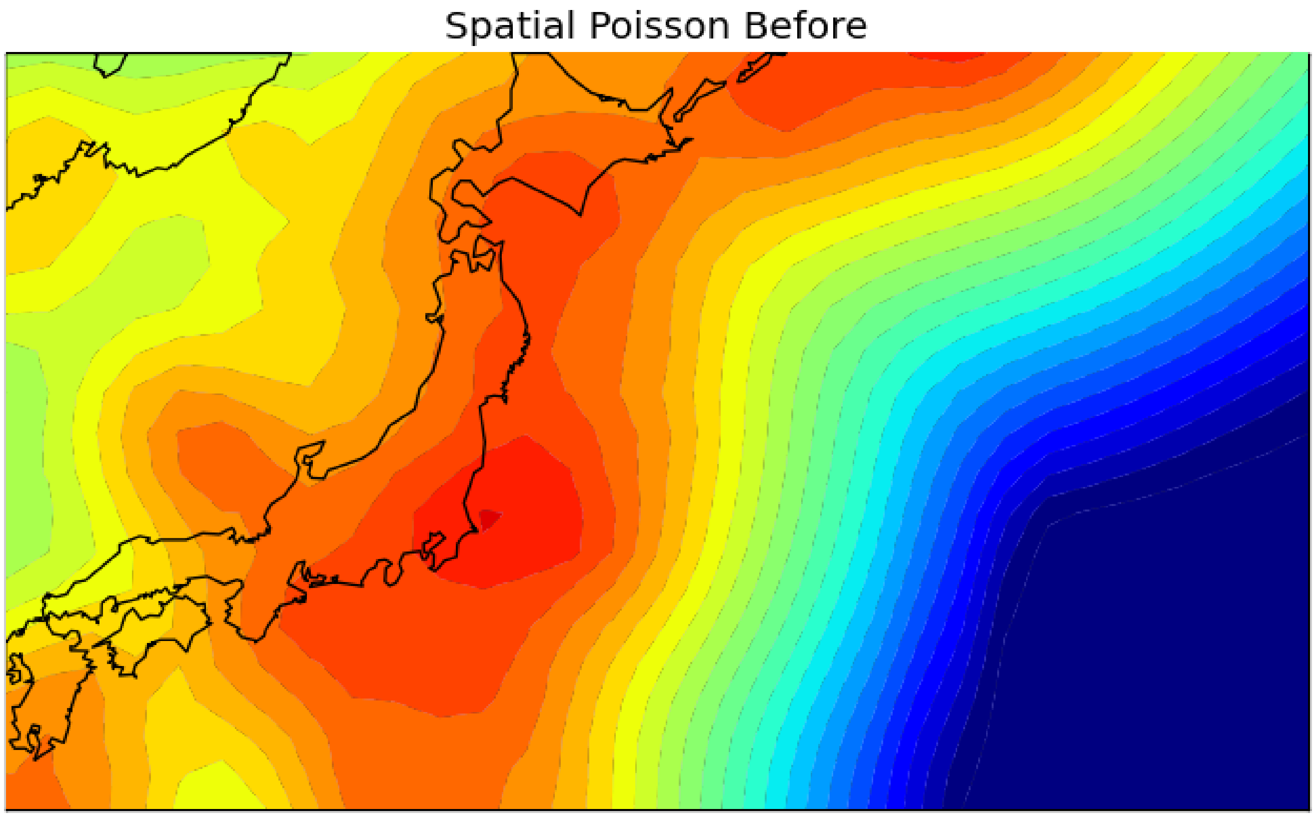
… after 3 months of data



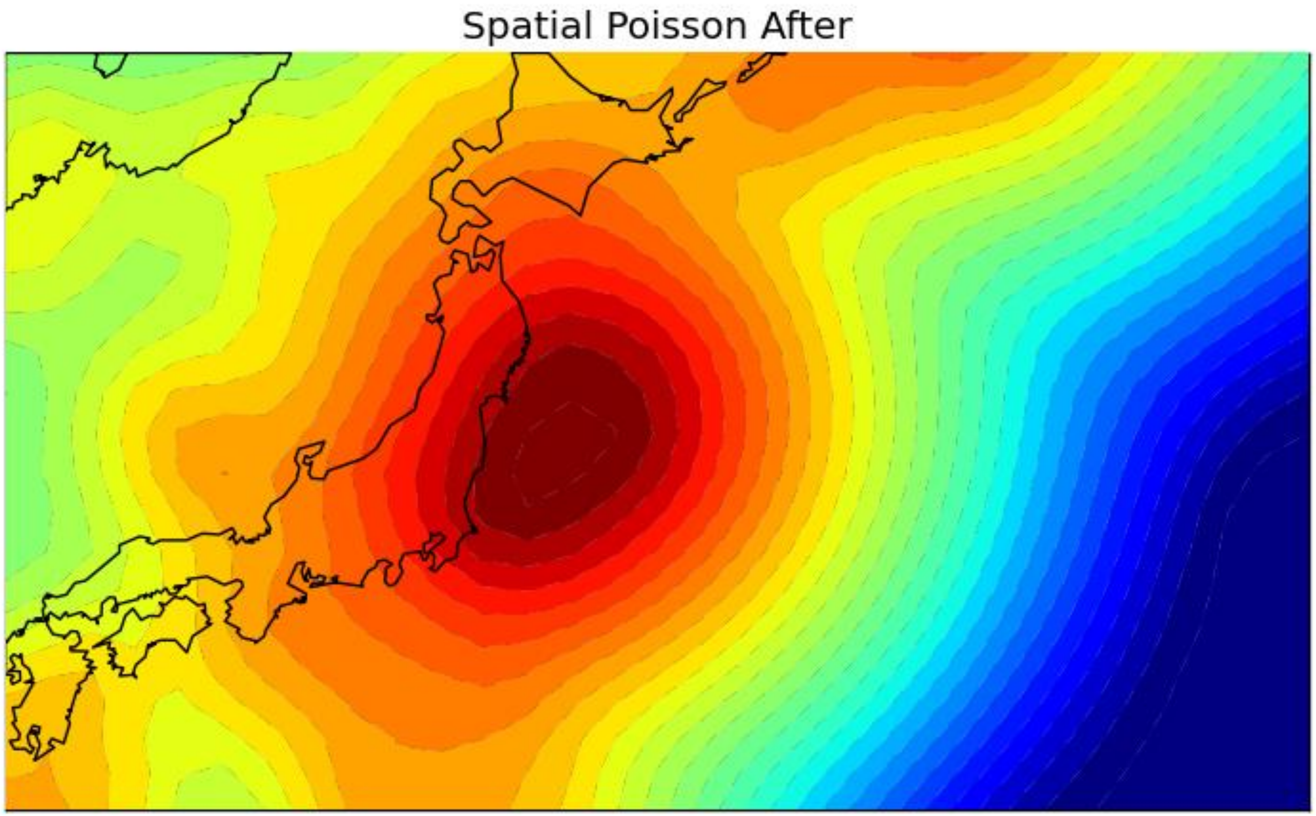
… 2 days after the Tohoku earthquake



… zooming into Japan … before



… and after…



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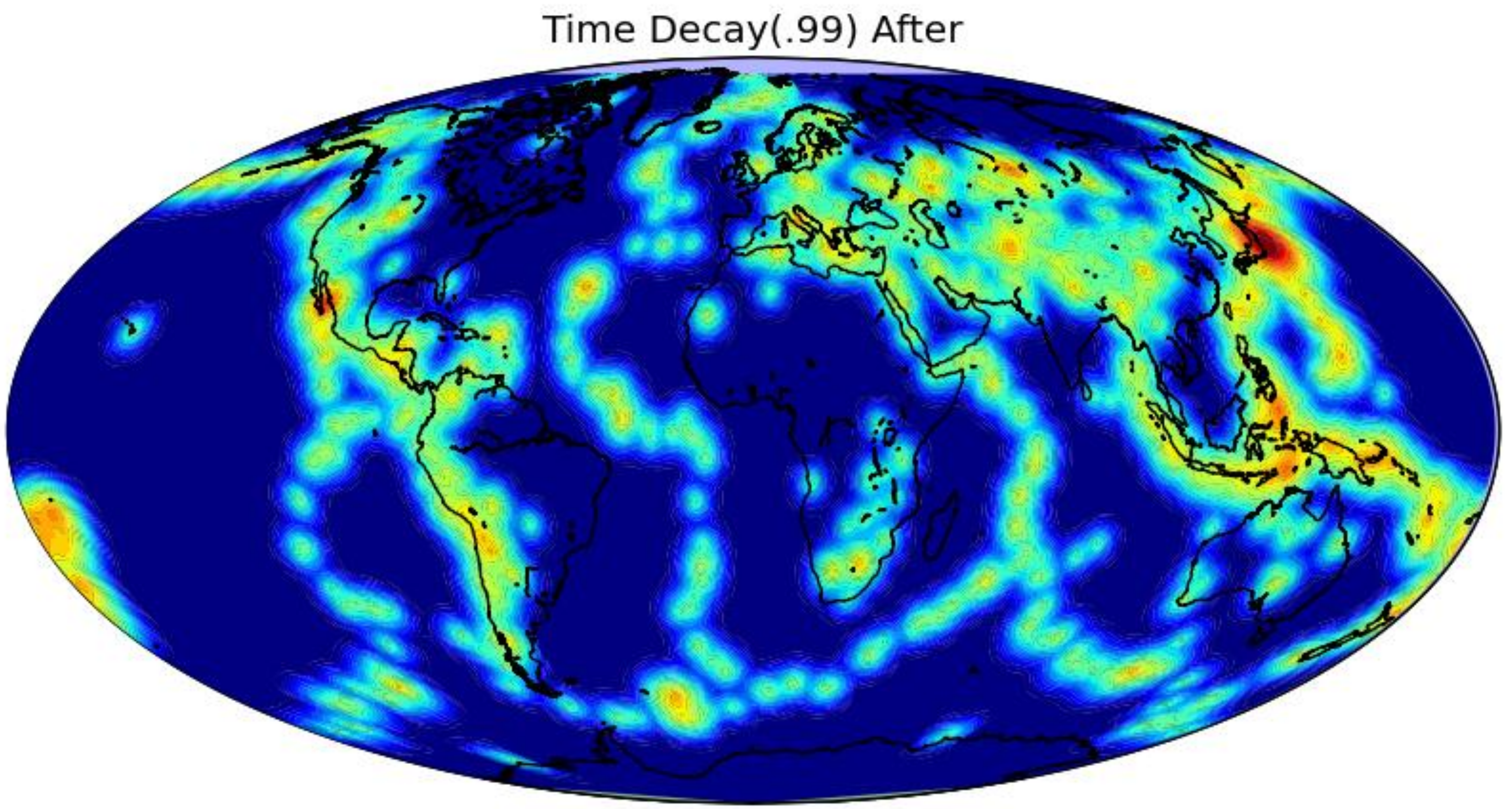
Exponential Decay with Time

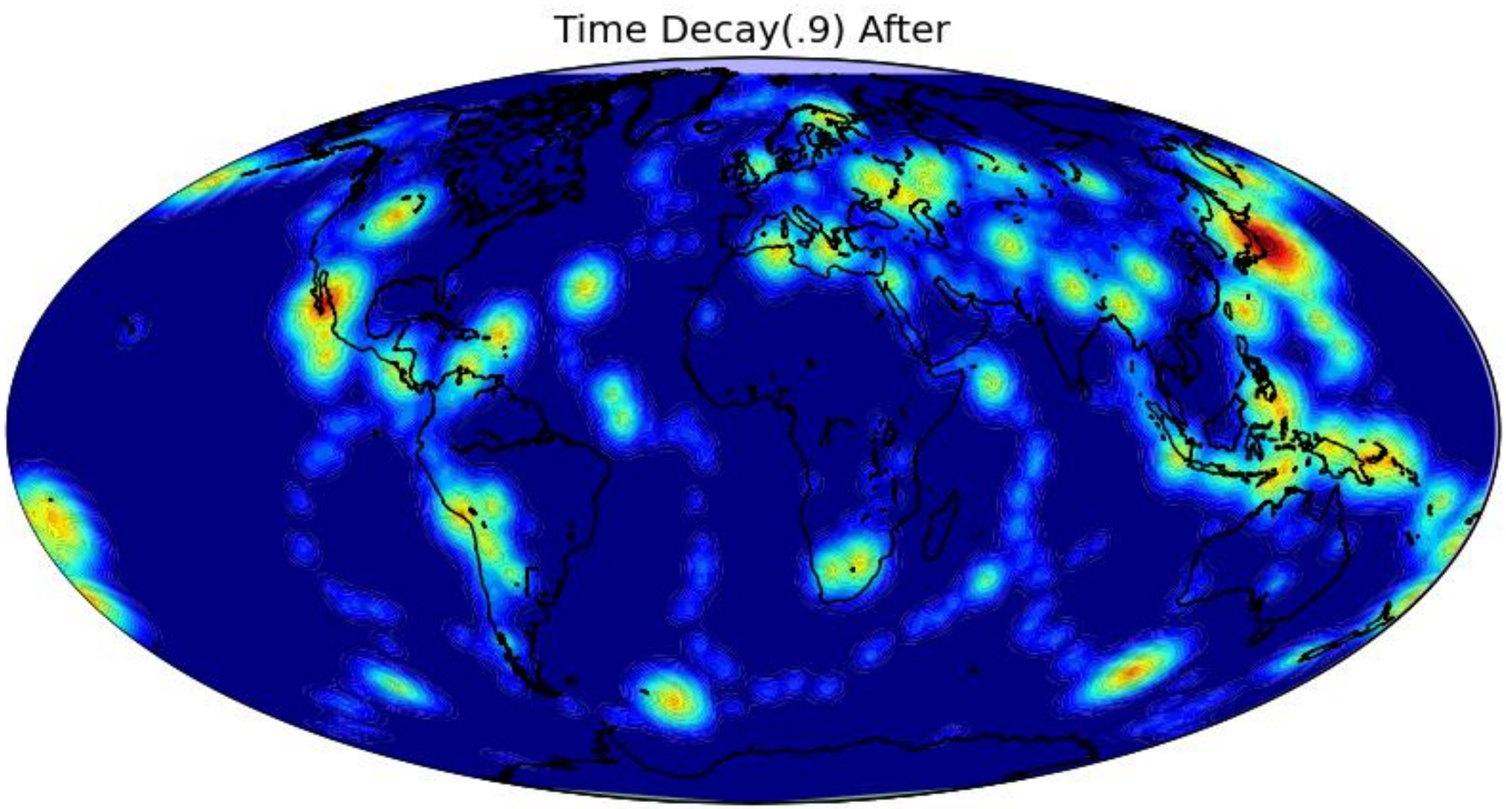
$$\lambda(y) = \sum_{i=1}^{n} K_{b,x_i}(y)(1-\alpha)\alpha^{T_i}$$

- T_i is time elapsed since event i
- alpha is the decay rate

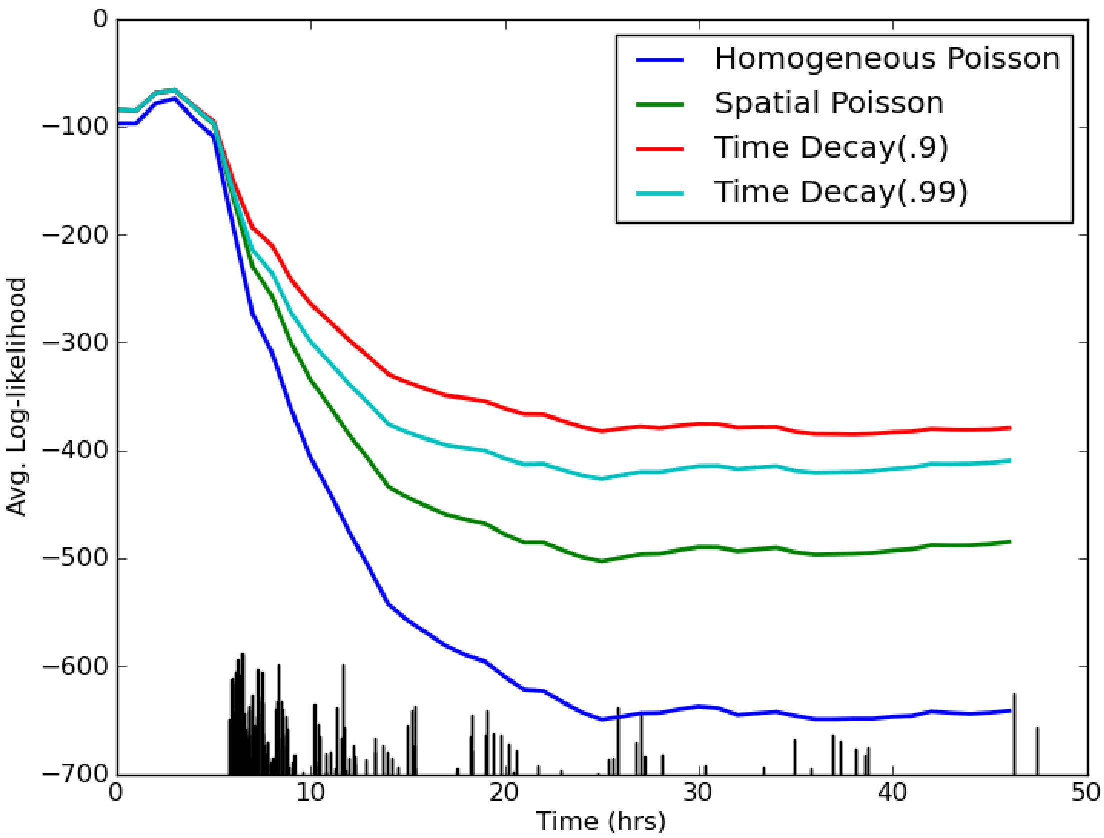
Exponential decay (rate = .99)



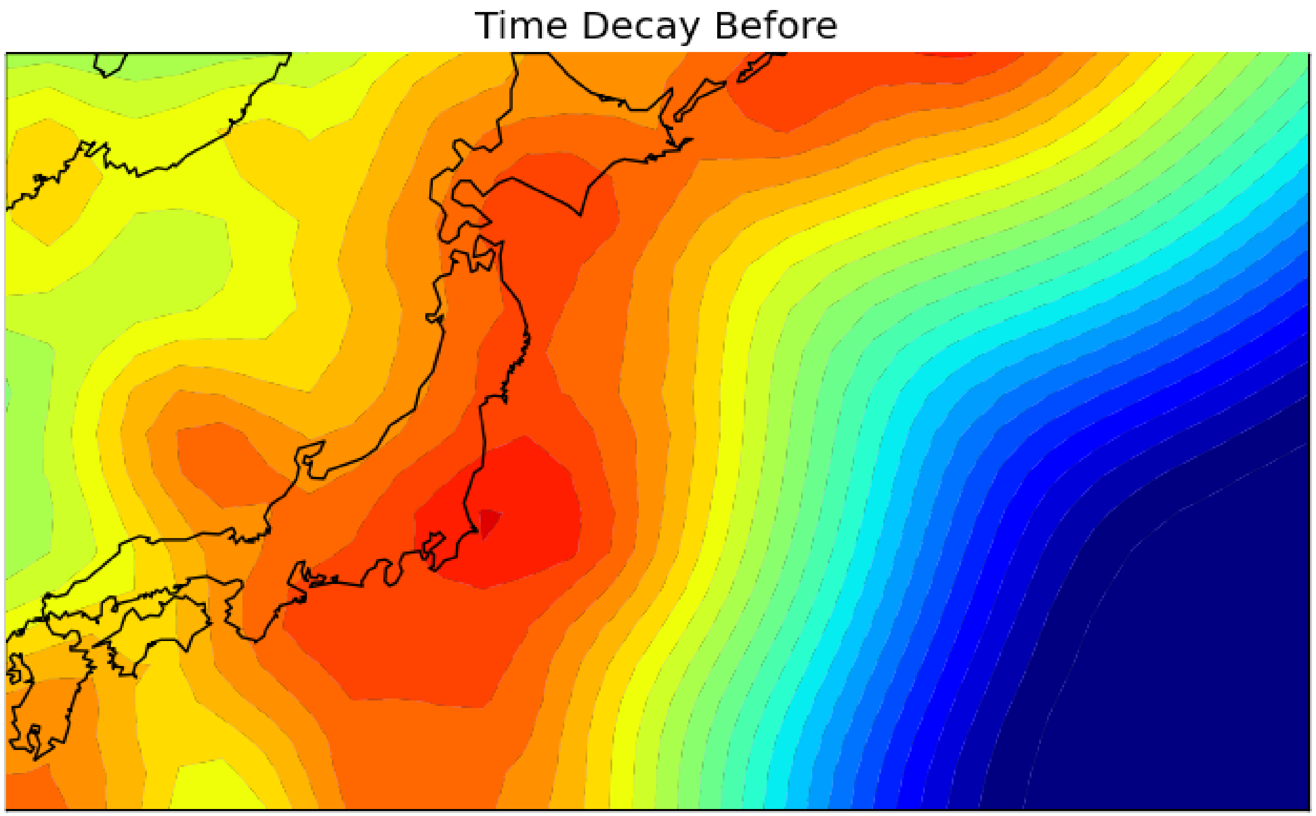
Exponential Decay (rate = .9)



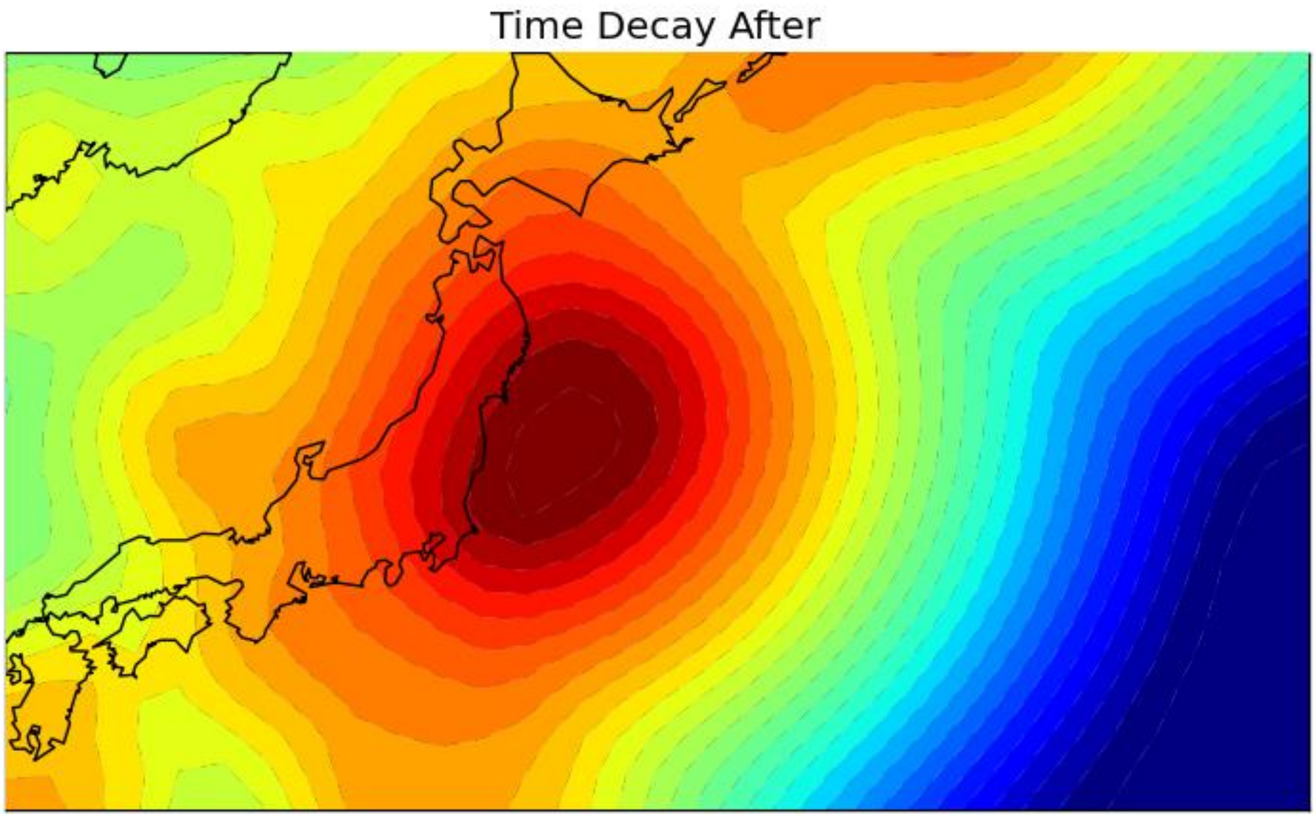
Log-likelihood on Tohoku Sequence



… before Tohoku…



… and after…



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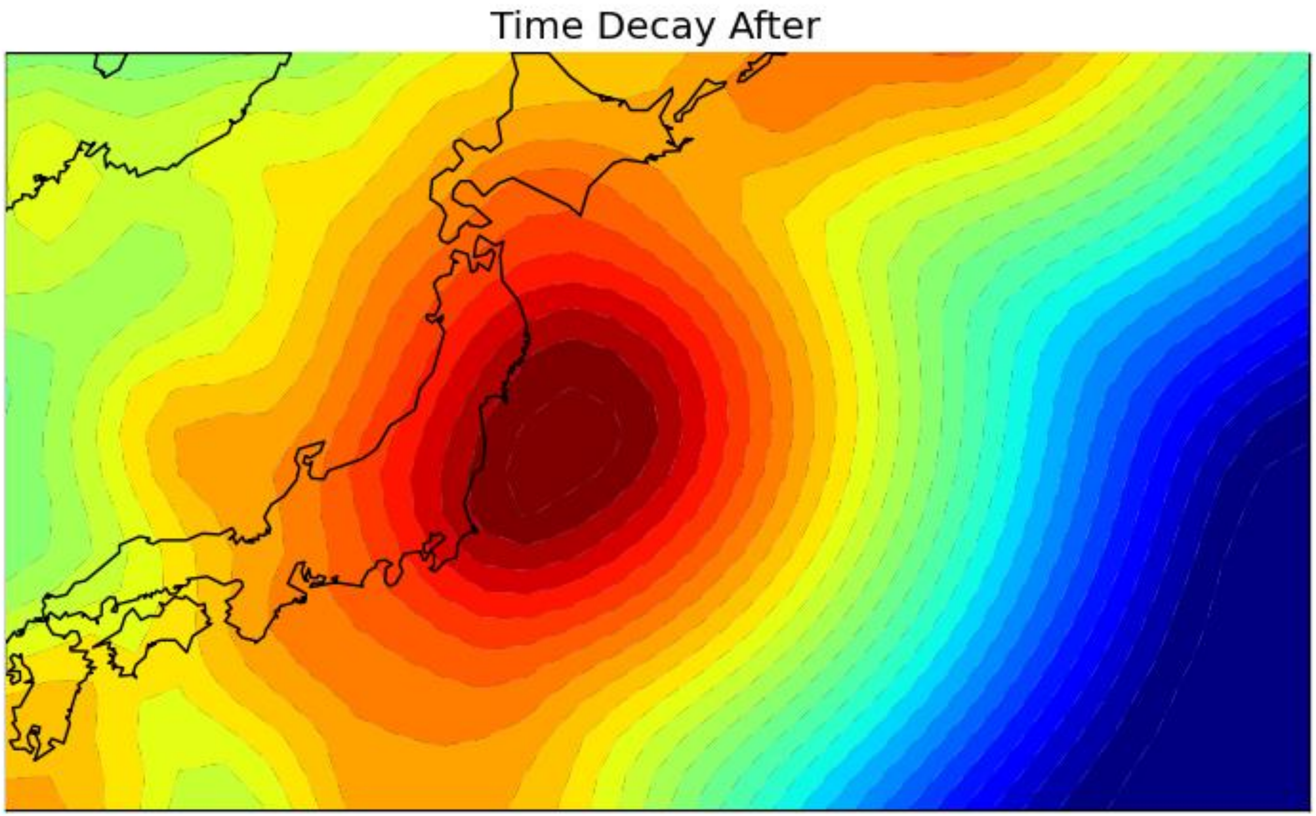
Taking event magnitude into account

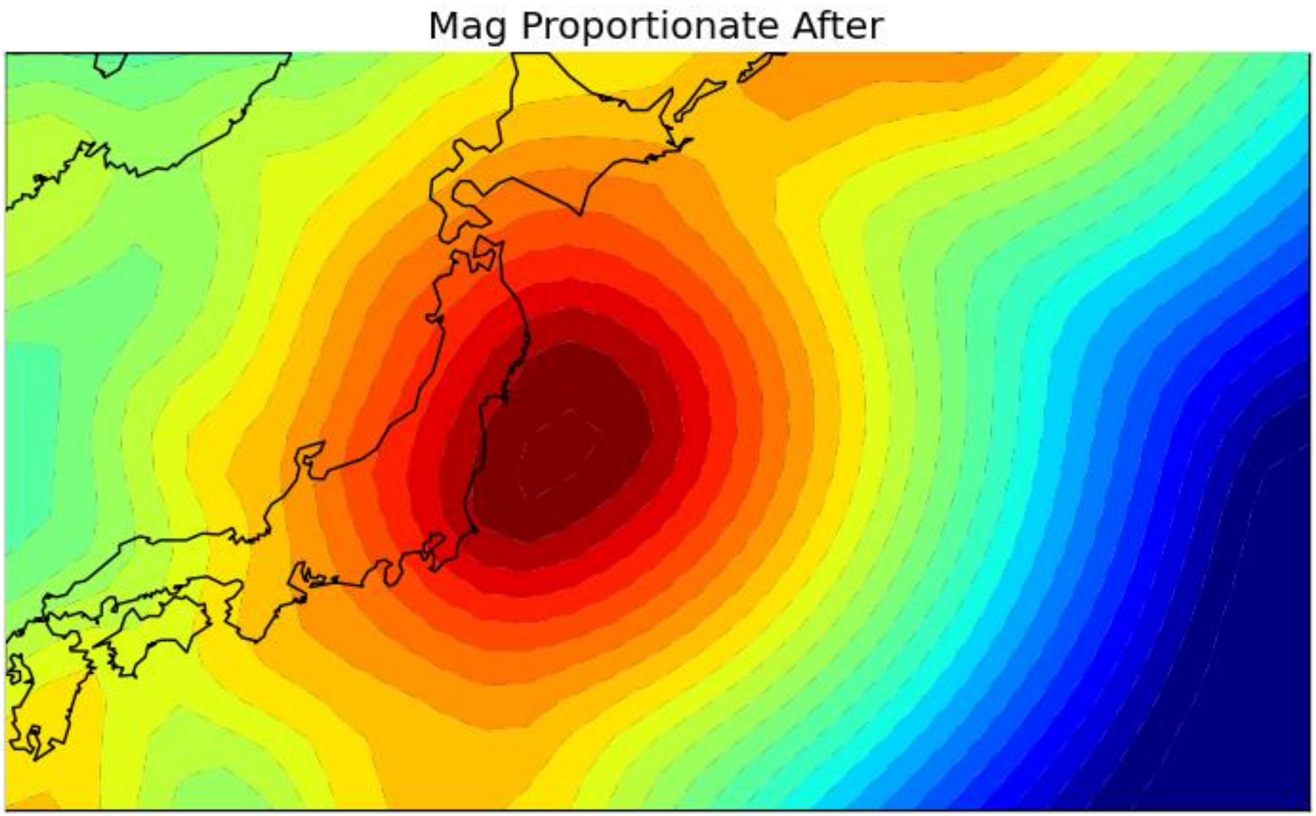
$$\lambda(y) = \sum_{i=1}^{n} K_{b,x_i}(y)(1-\alpha)\alpha^{T_i} e^{m_i - 3.5}$$

- m_i is the magnitude of the event i

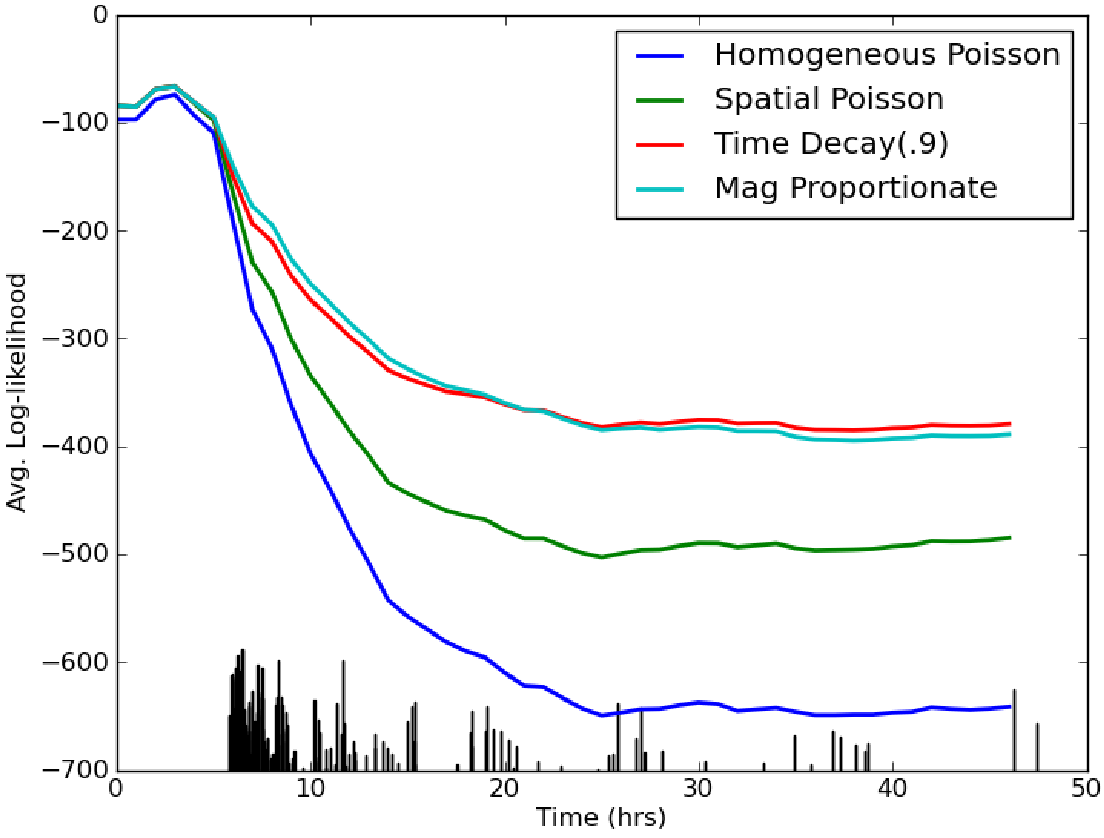
Time decay versus…



Time decay + magnitude



Proportional to Magnitude



Conclusion

- Events produce aftershocks with rate decaying exponentially with time
- For rate estimation, the magnitude of a large event is not as important since the initial aftershocks can be used to estimate the subsequent aftershock rate!
- Alternate approach: maintain history of recent (space and time) events for each location to compute density on demand. Allows usage of Omori's law.