Bayesian Monitoring in VISA: Results and Plans

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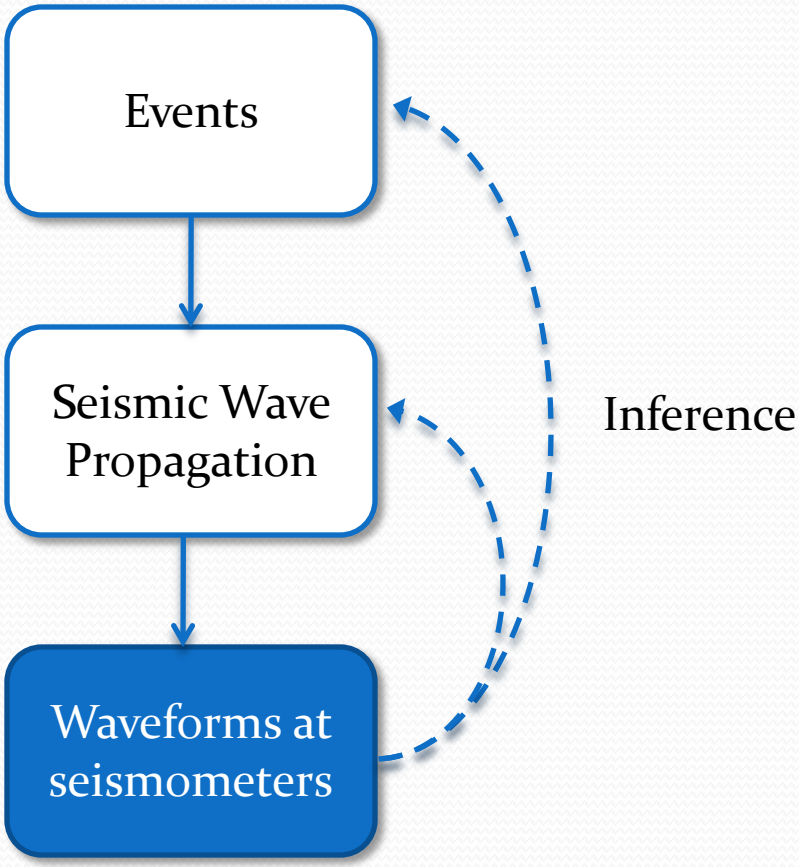
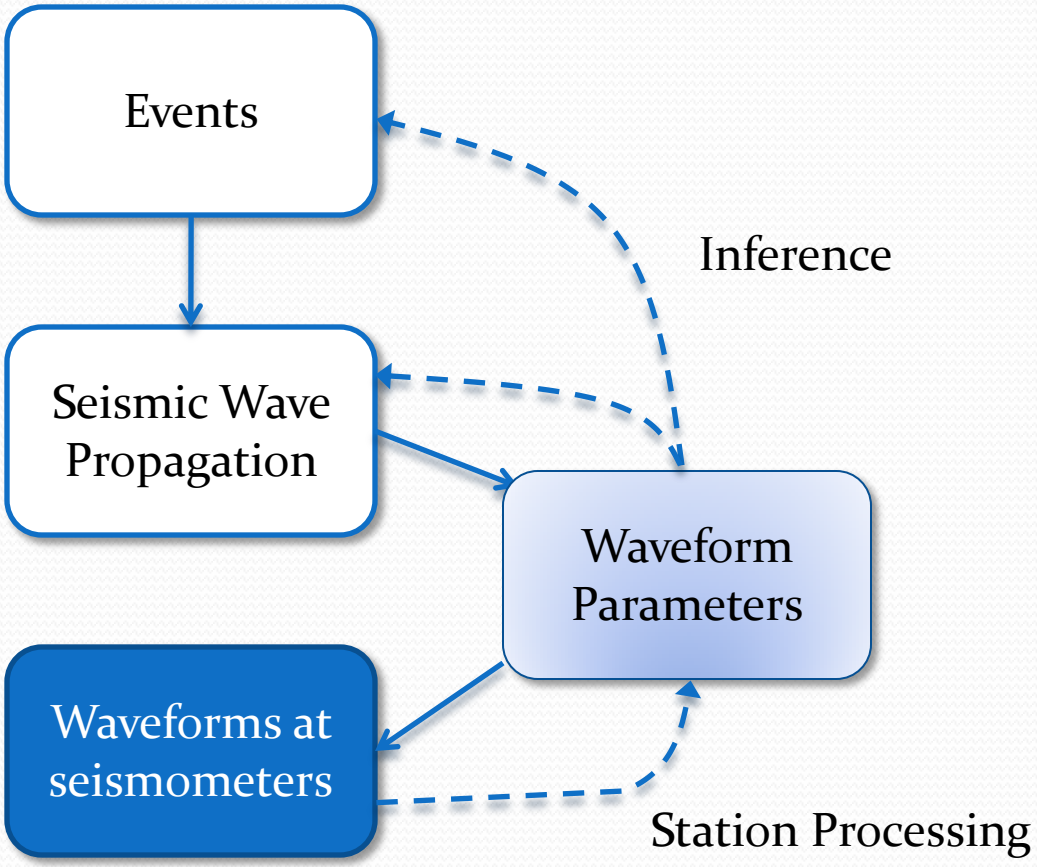
Vertically Integrated Seismic Analysis (VISA)



Network Processing (NET-VISA)



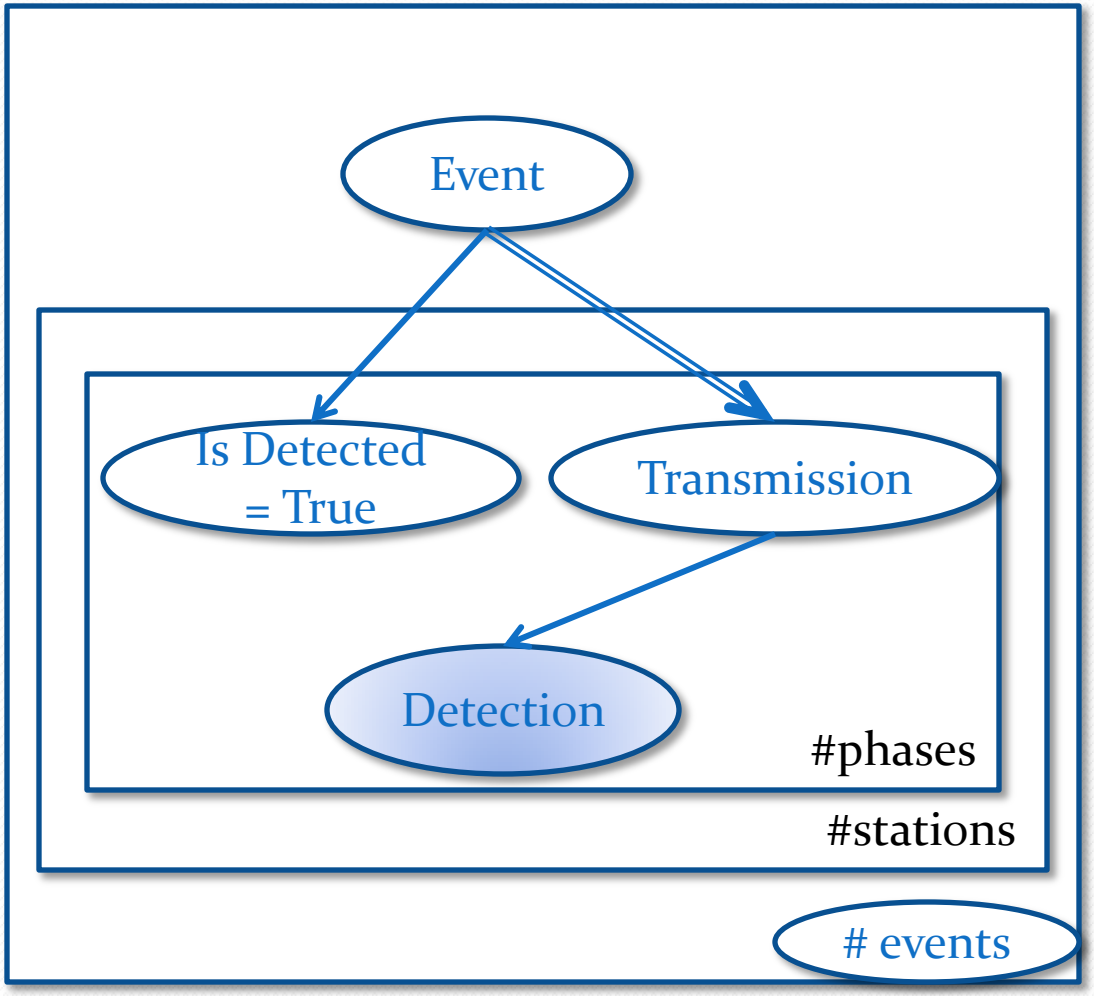
Overview

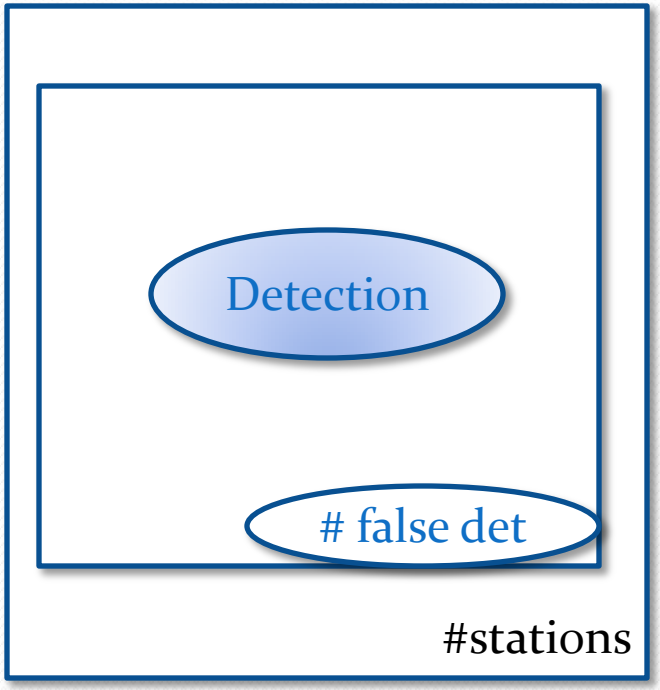
- Generative Probabilistic Model
- Inference
- Results
- Analysis
- Future plans

NET-VISA model: variables

- 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]

Generative Model





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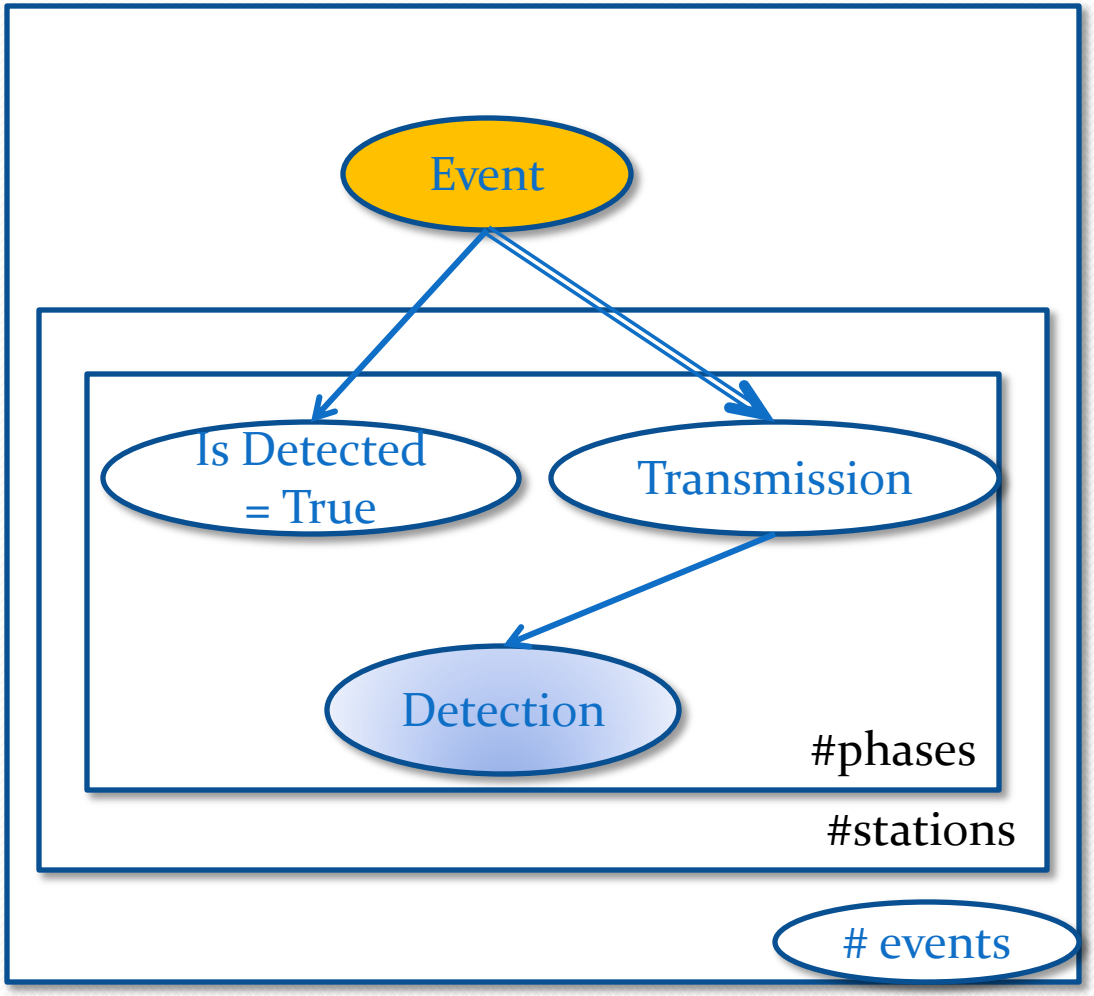
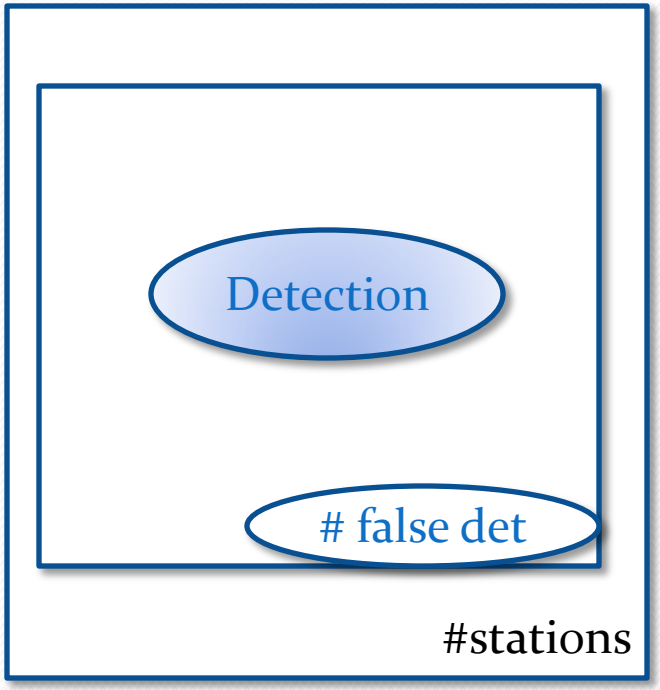


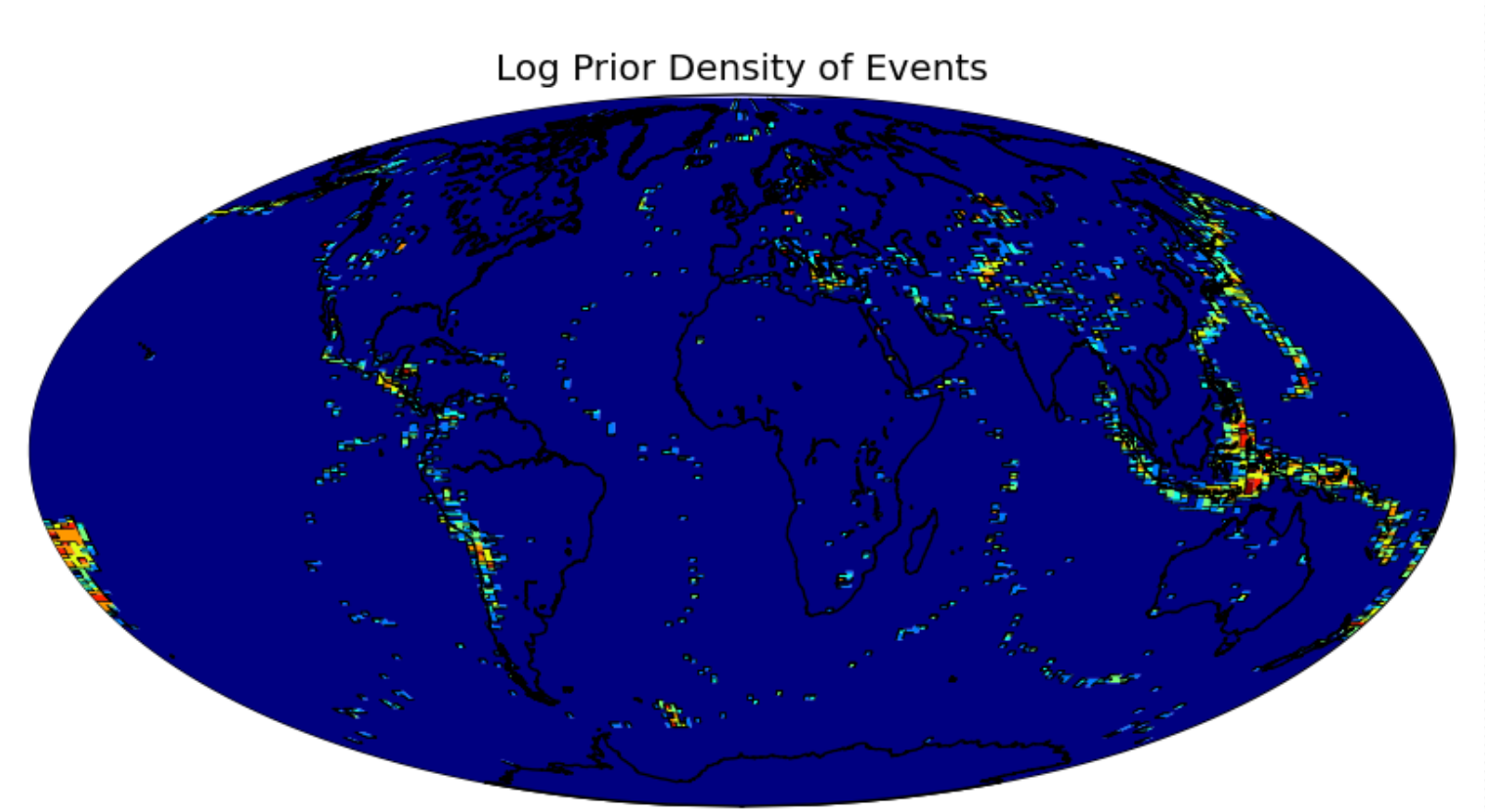


Event Prior

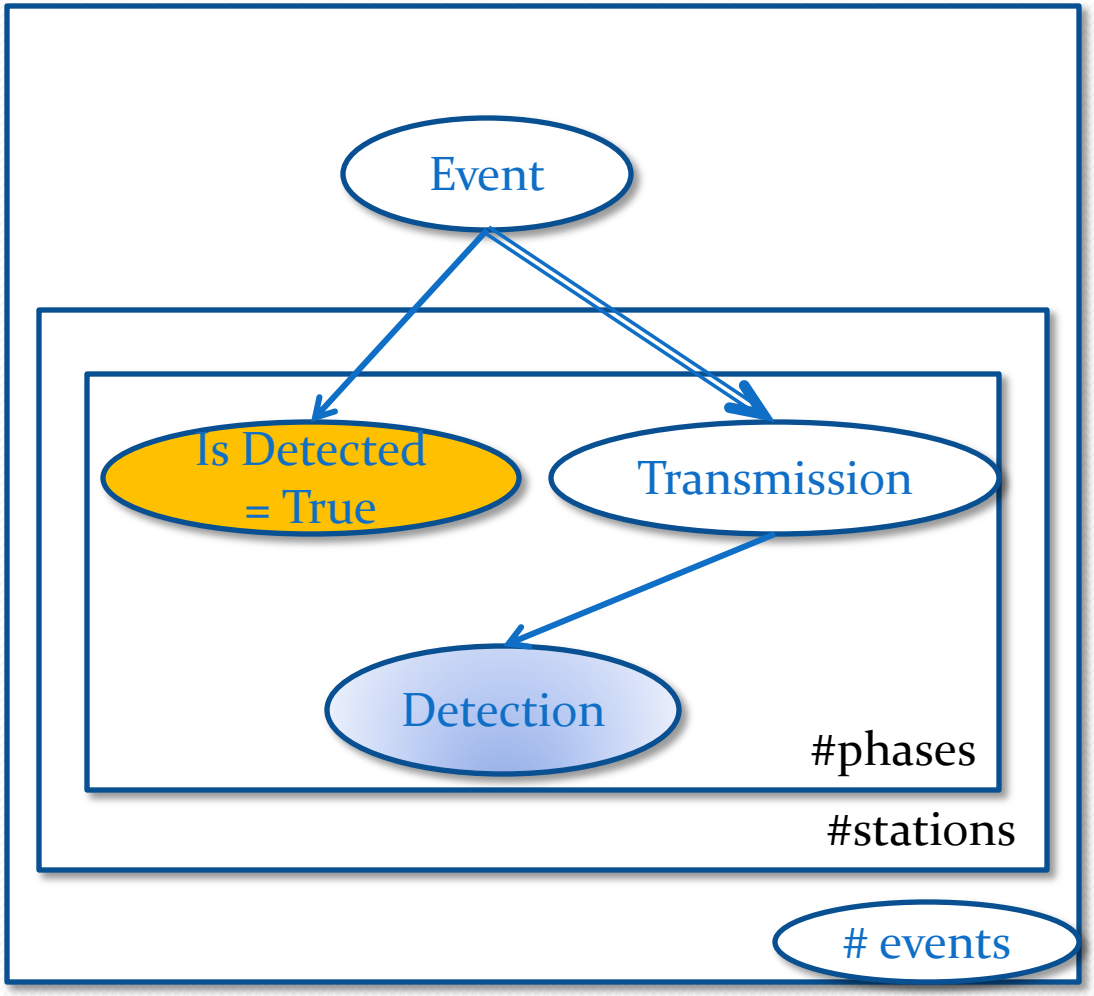
- Event magnitude is given by a Gutenberg Richter distribution
- Depth is assumed to be uniformly distributed (0 – 700 km)

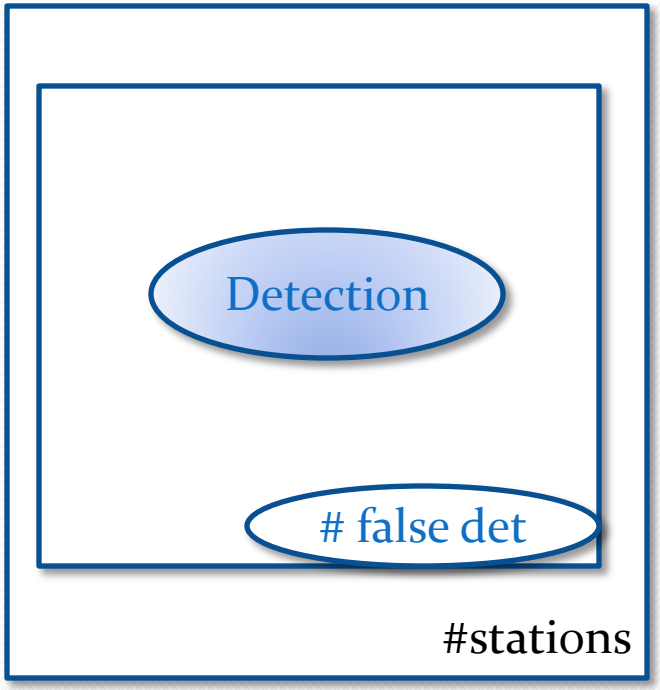
Event Location Prior 2 deg buckets

- Simple histogram for 2 degree buckets over the surface of the earth. Absolute discount smoothing – similar to mixing with a uniform distribution



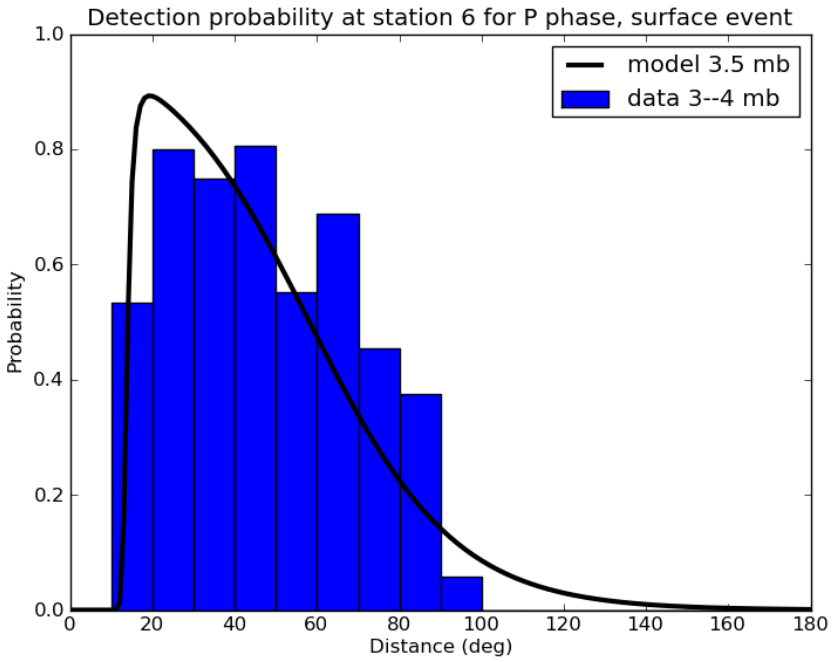
Generative Model

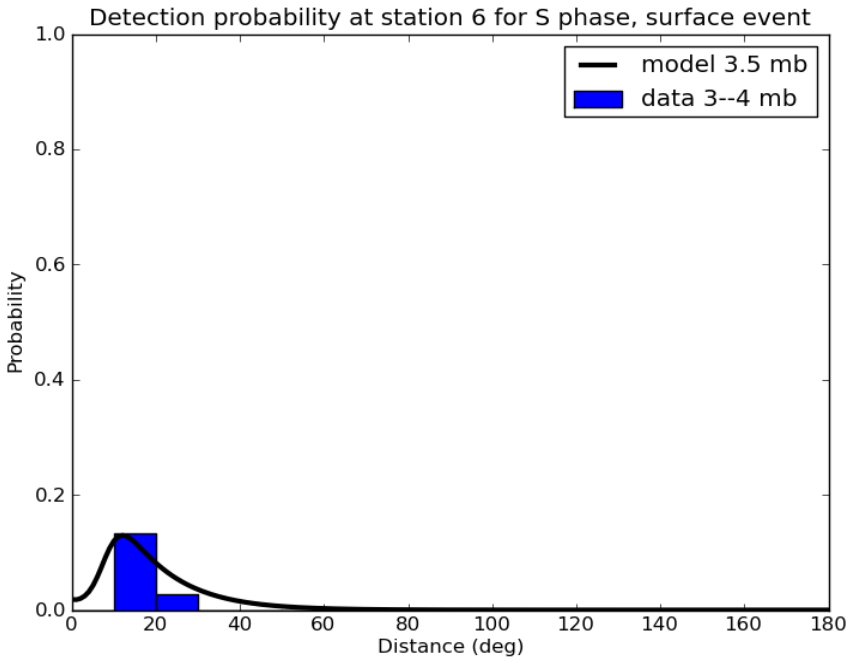




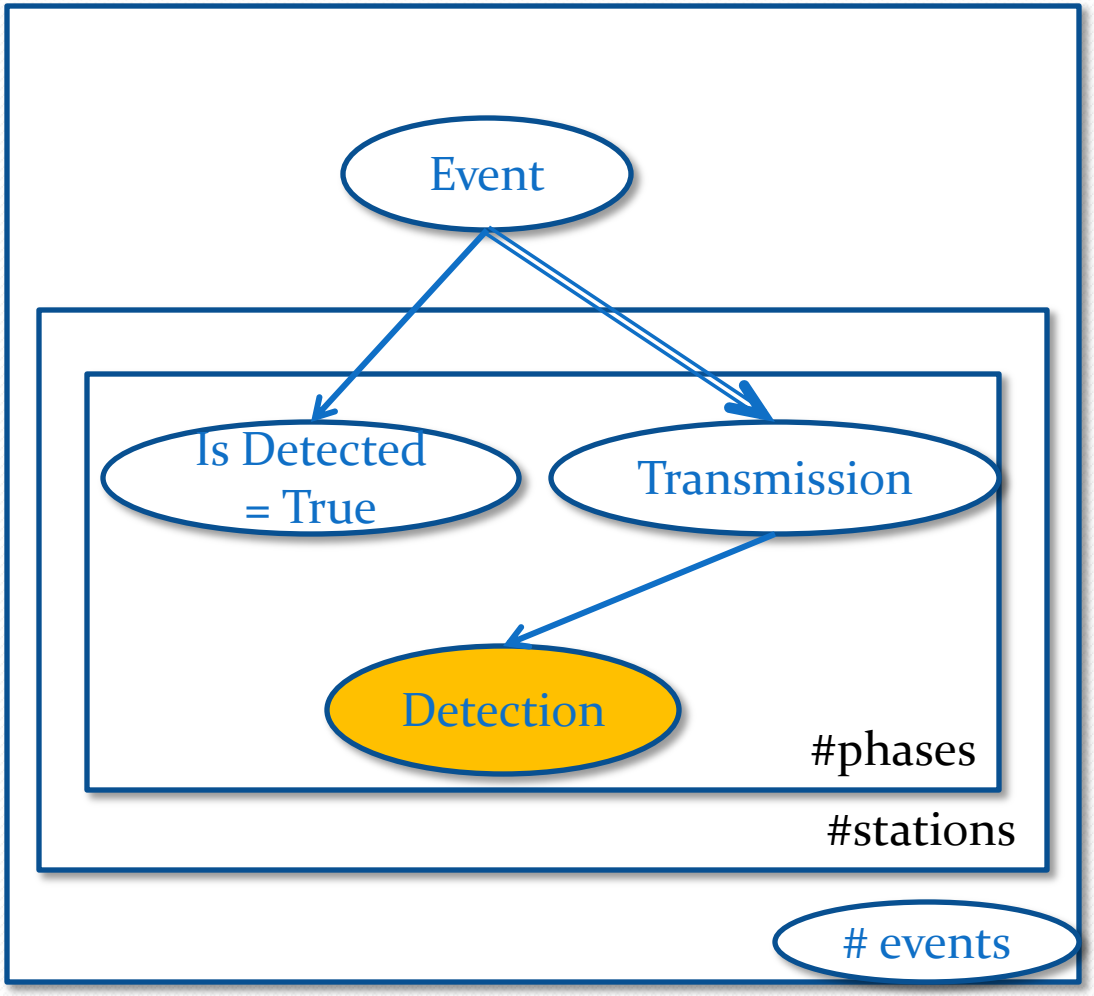
Detection Model

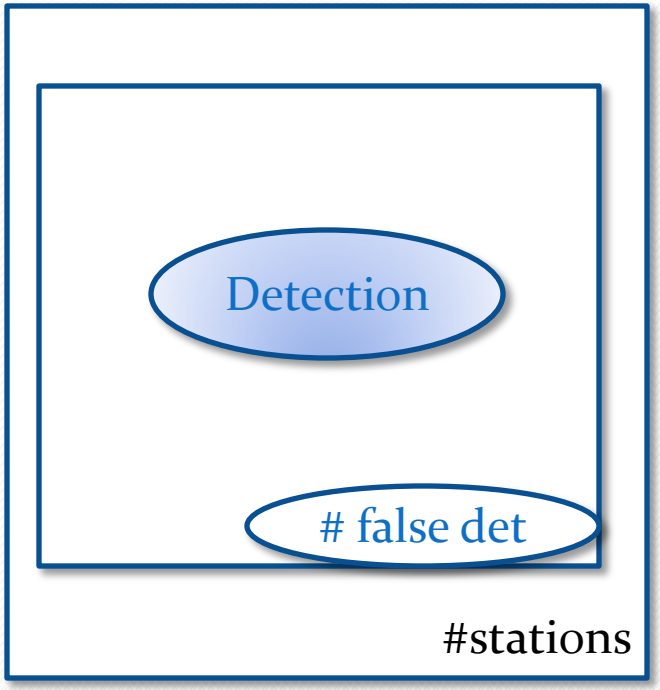
- Logistic Regression using event magnitude, depth, and distance to station as basic features
- Various combinations of the basic features



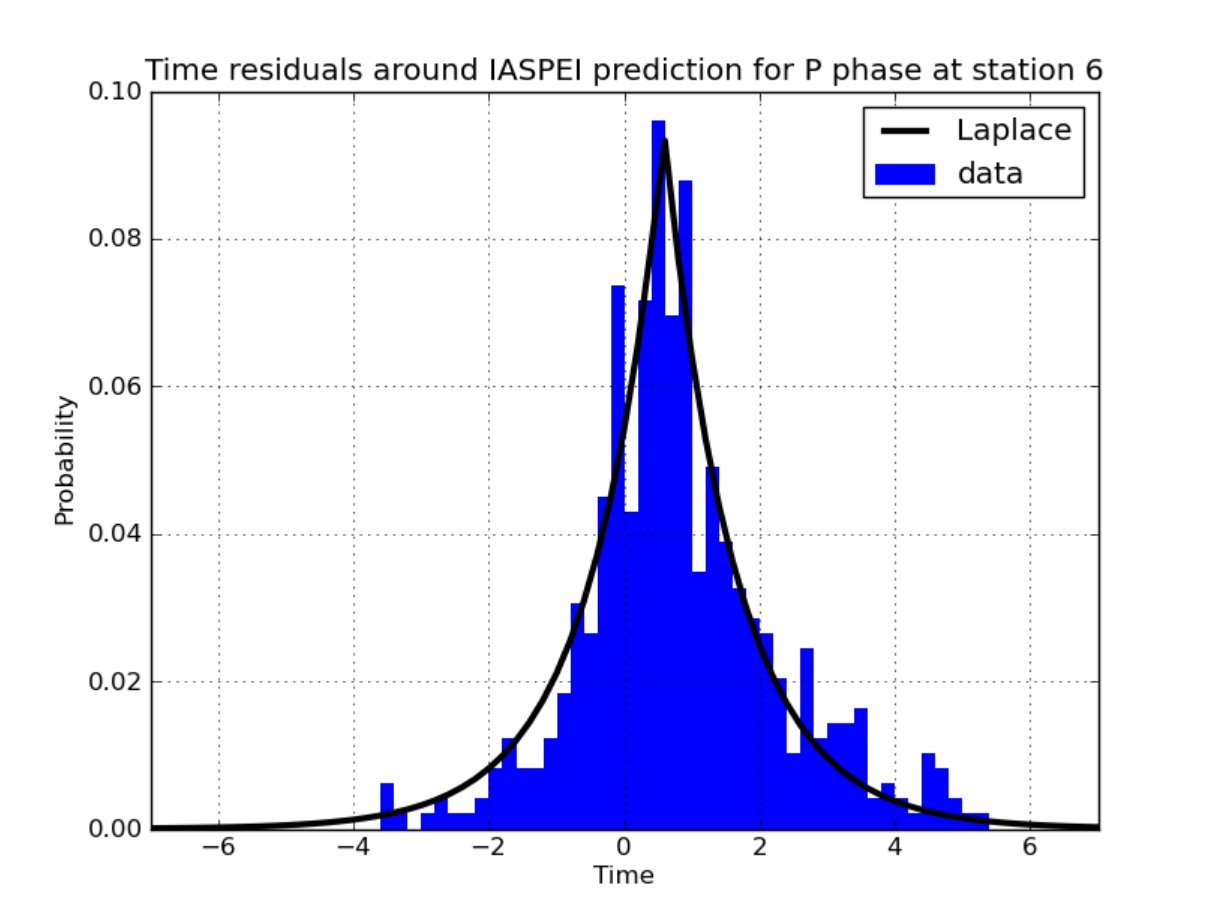


Generative Model

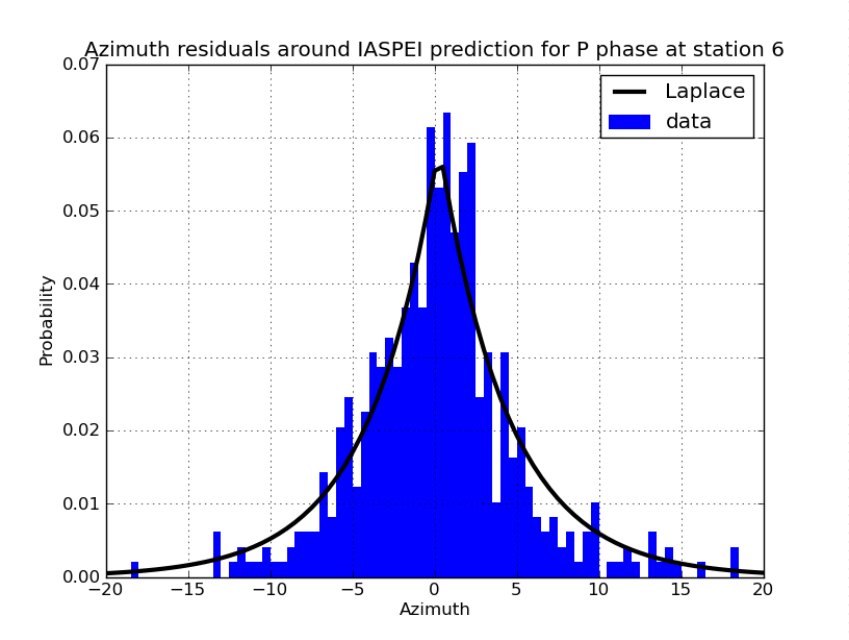


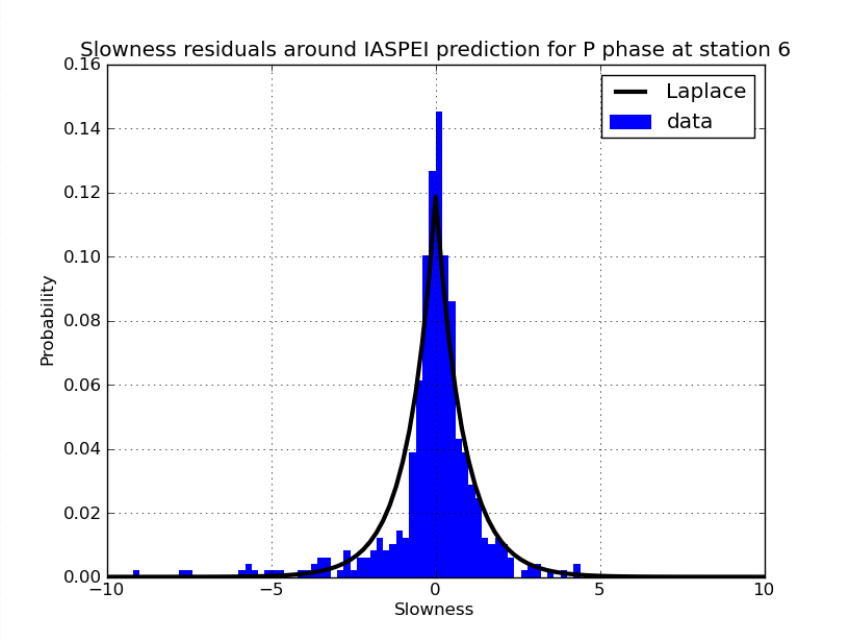


Arrival Time – Laplacian Distribution



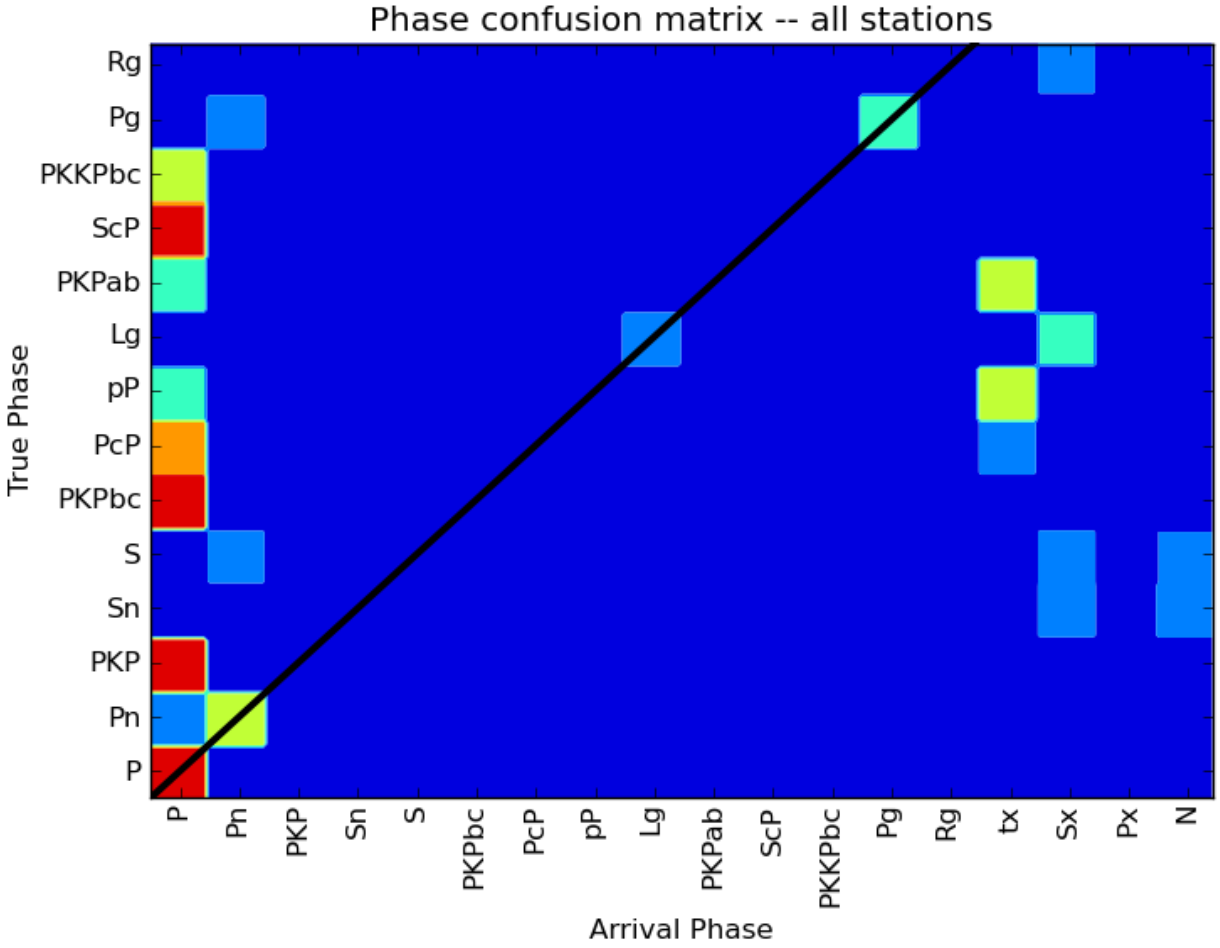
Arrival Azimuth and Slowness .. also Laplacian





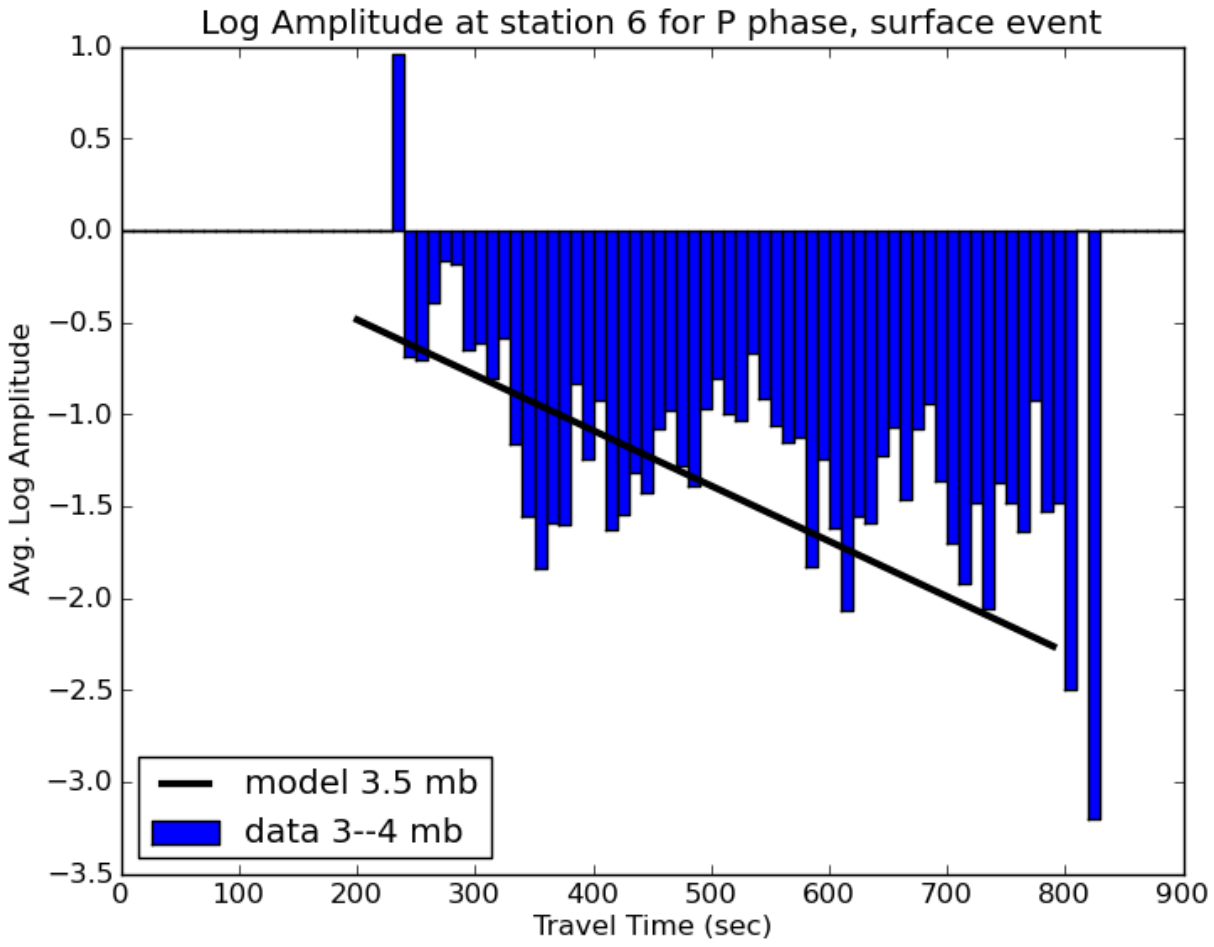
Arrival Phase

- Arrival phase is a multinomial conditional on the true phase

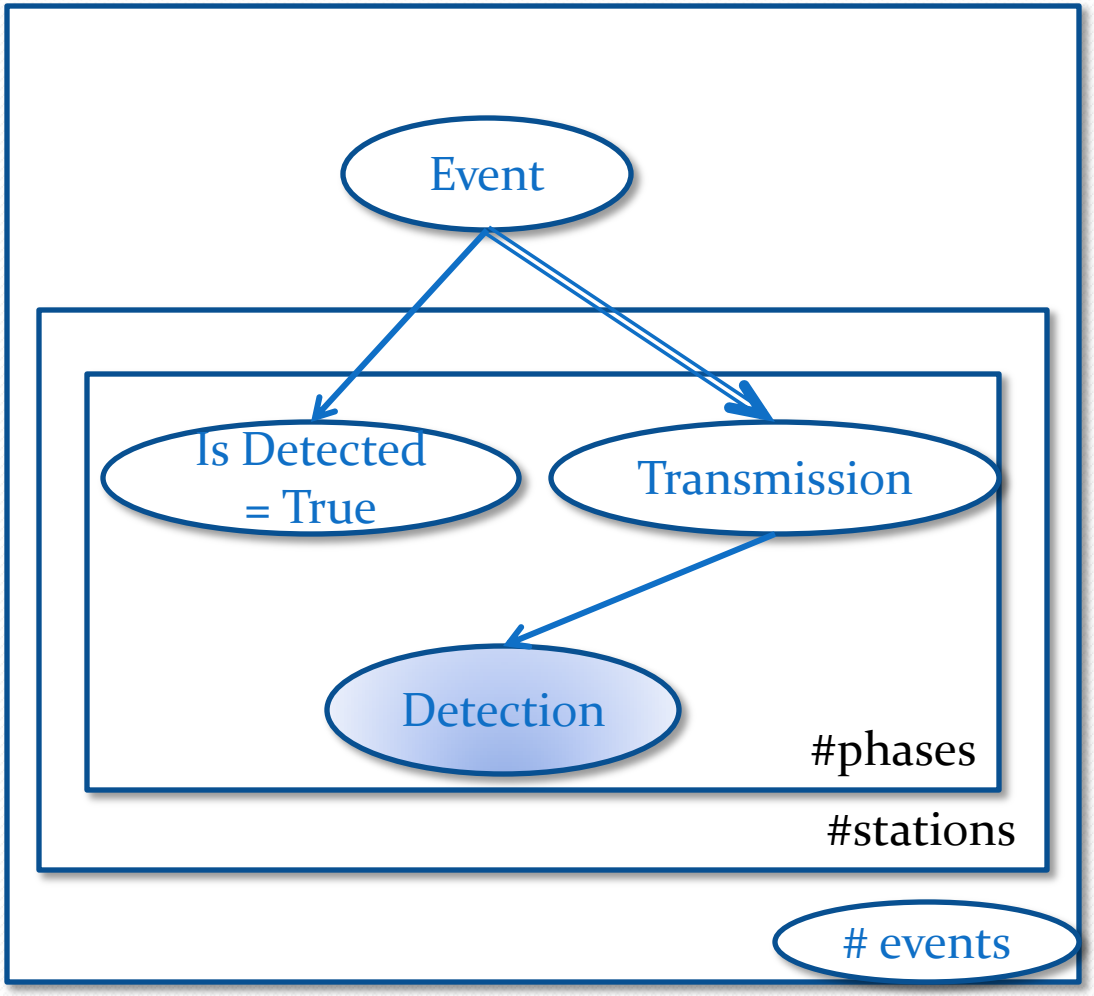


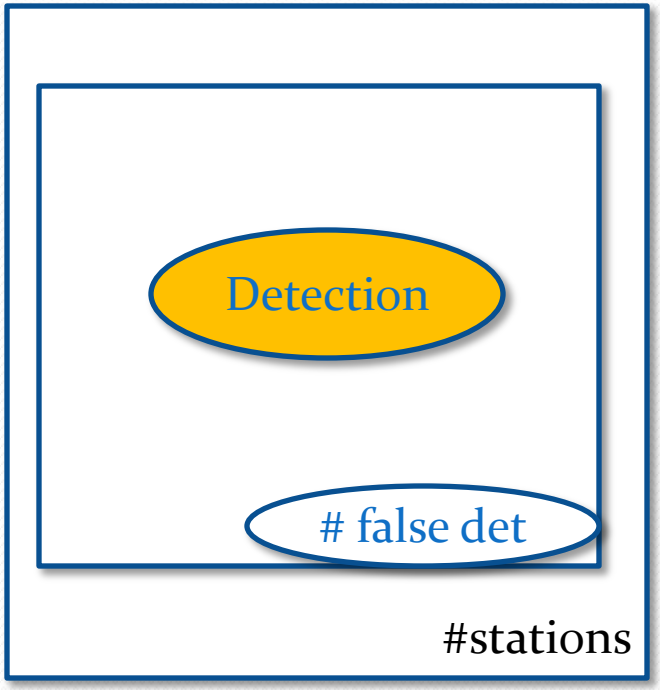
Arrival Amplitude

- Log-amplitude is a linear model of event magnitude, depth, and travel time



Generative Model



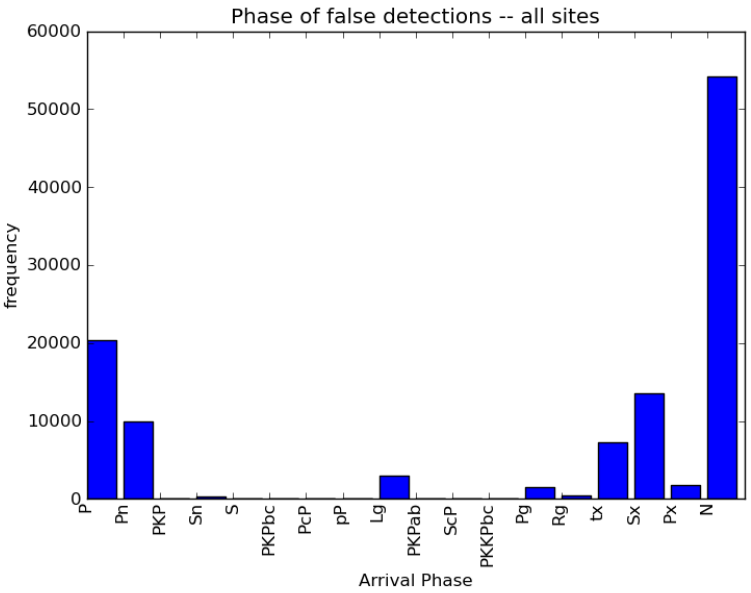


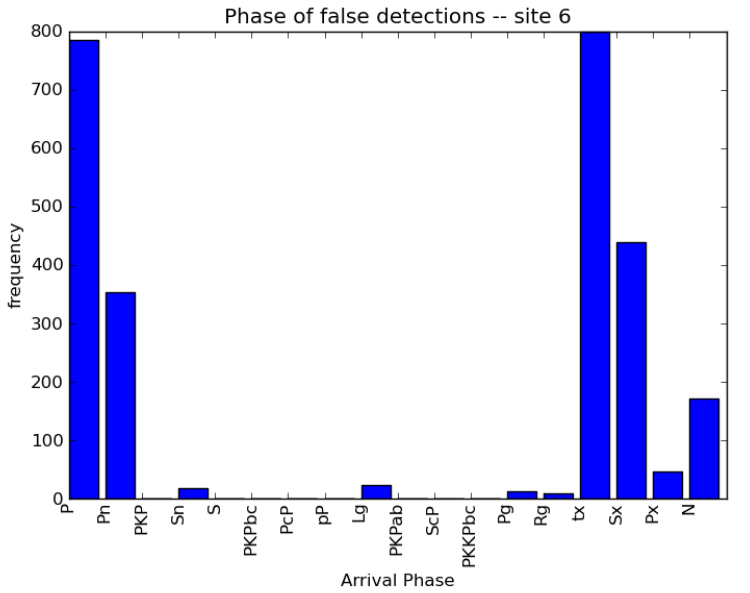
False Arrival Model

- Time, Azimuth, and Slowness are uniformly distributed

False Arrival : phase distribution

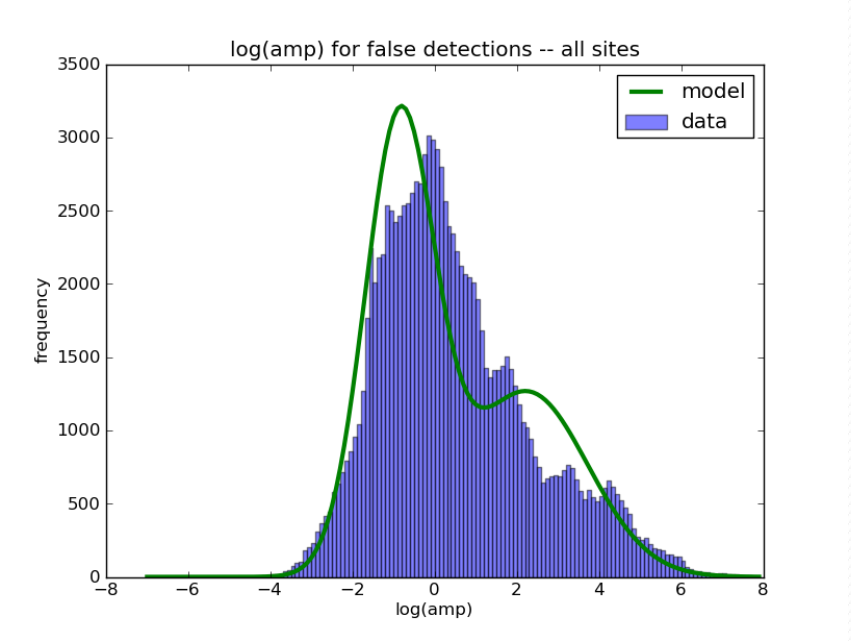
- Phase has a multinomial distribution

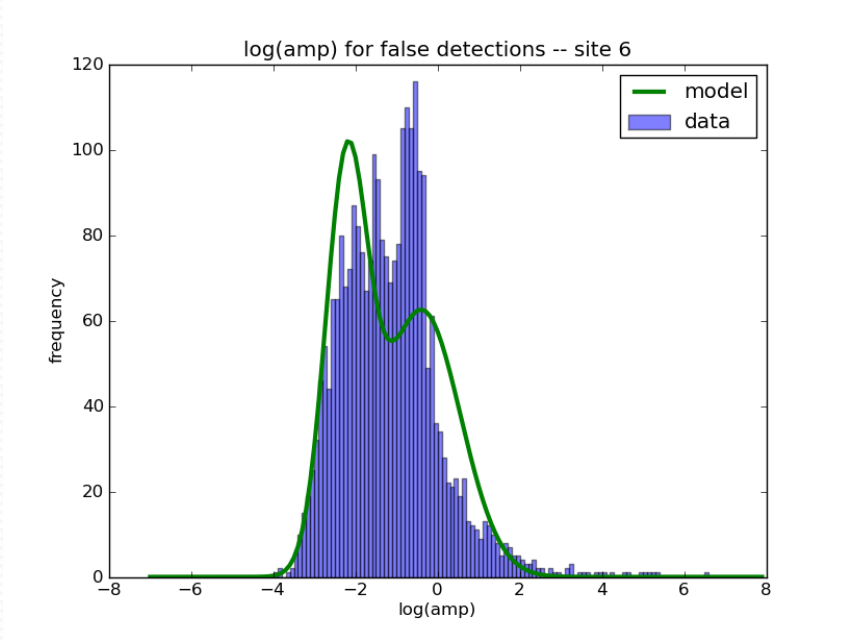




False Arrival: amplitude distribution

- Log-Amplitude is a mixture of two Gaussians





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Inference

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  - Location (longitude, latitude)
  - Depth
  - m_b
  - Time
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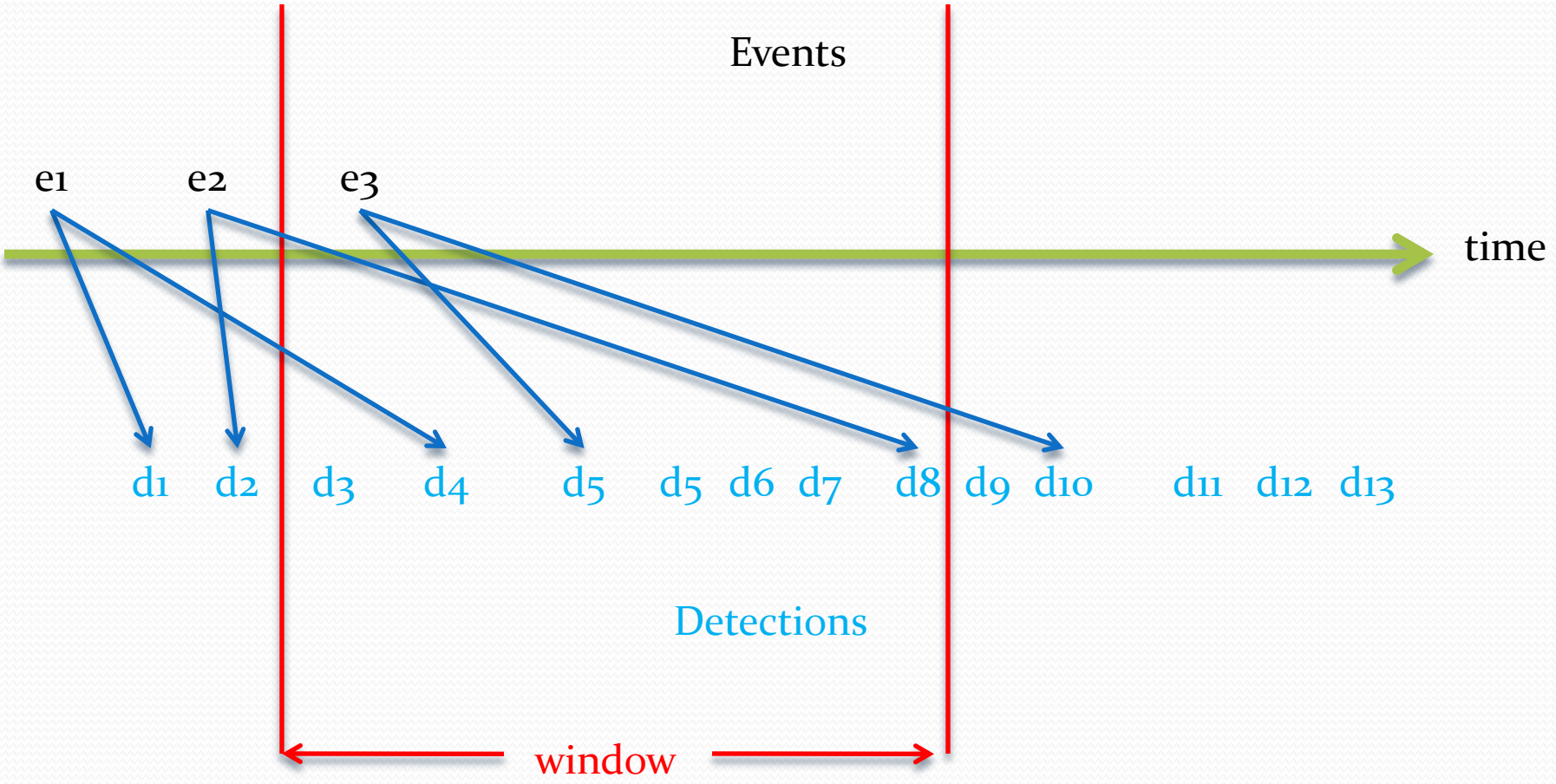
MAP Inference

- A hypothesis is a complete sequence of events and the detections associated to them
- *Max a-posteriori* (MAP) hypothesis is the single most probable explanation as per the model
- Easier to compare to SEL3
- Future MCMC inference can use MAP as an initializer

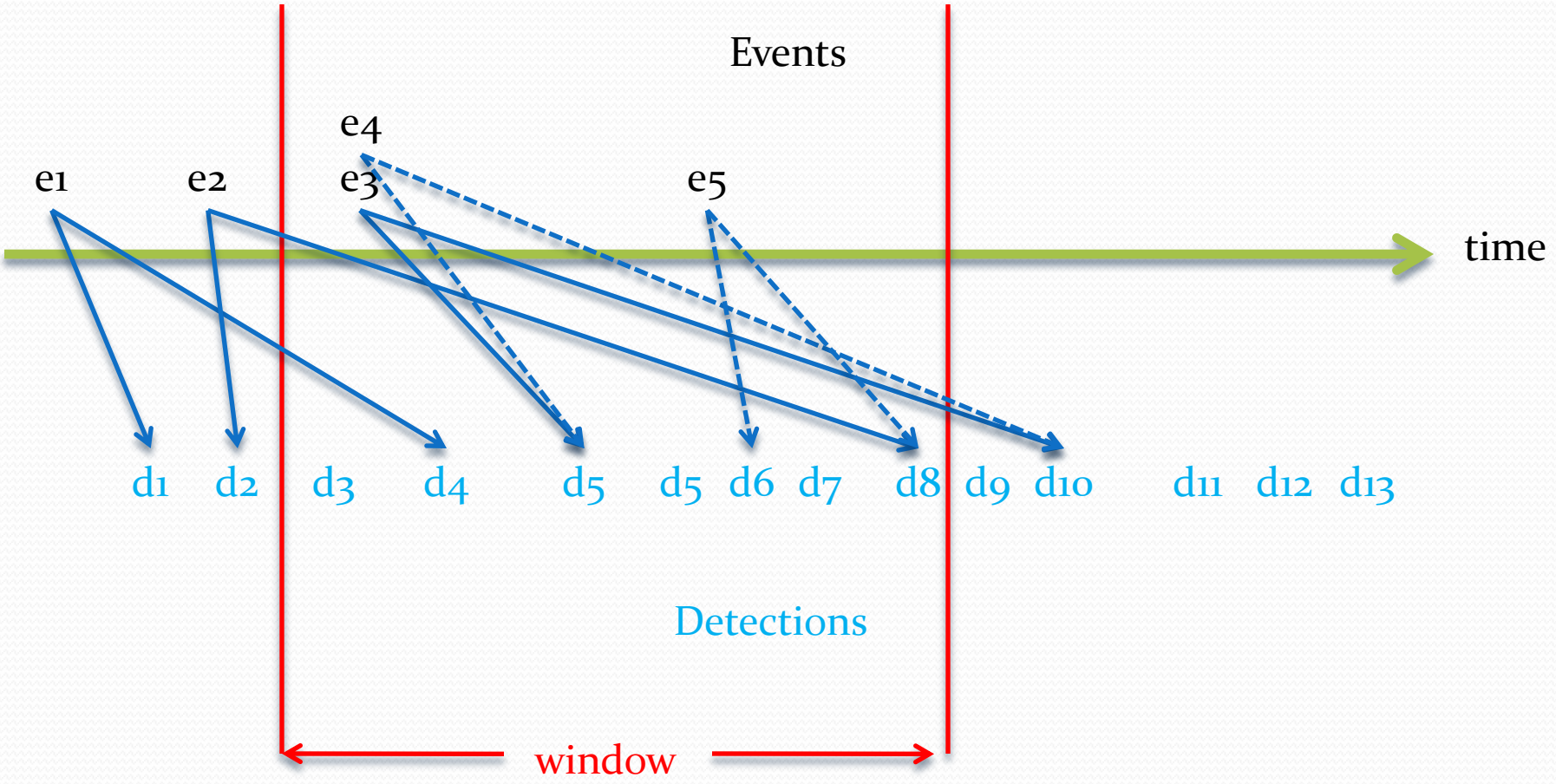
Inference Overview

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

Inference Example



Inference : Birth Move



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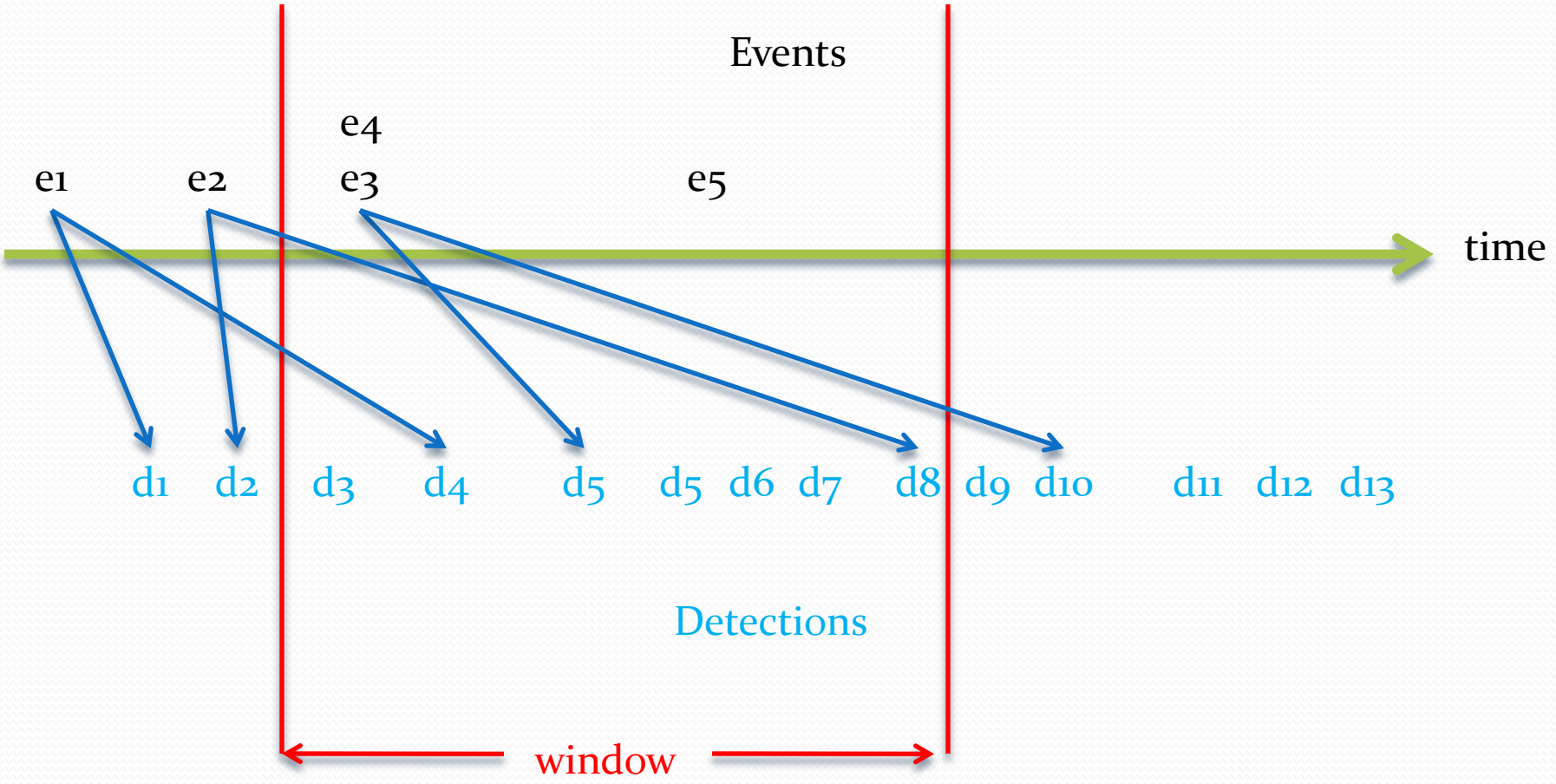
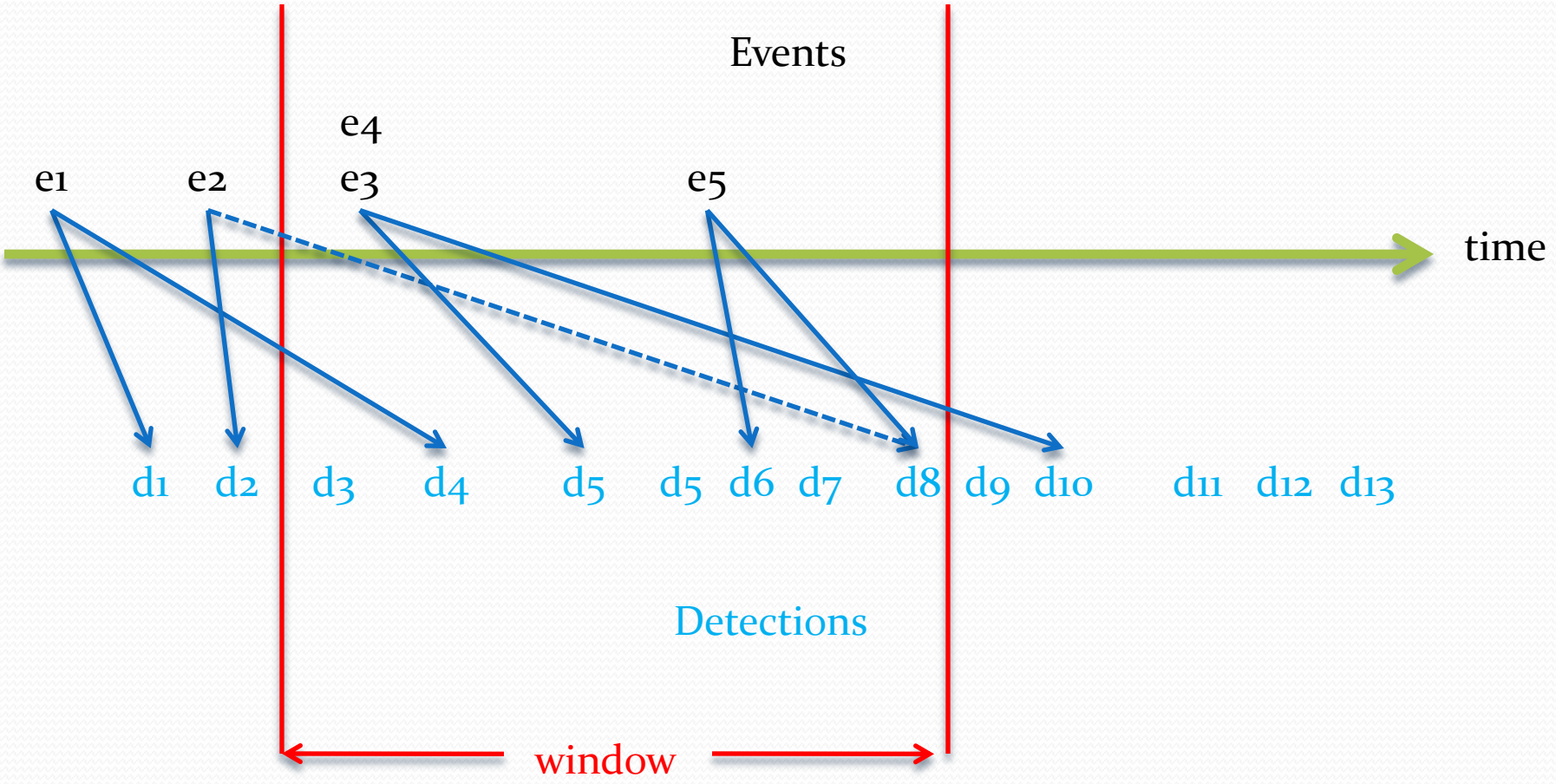


Inference : Reassociate Detections



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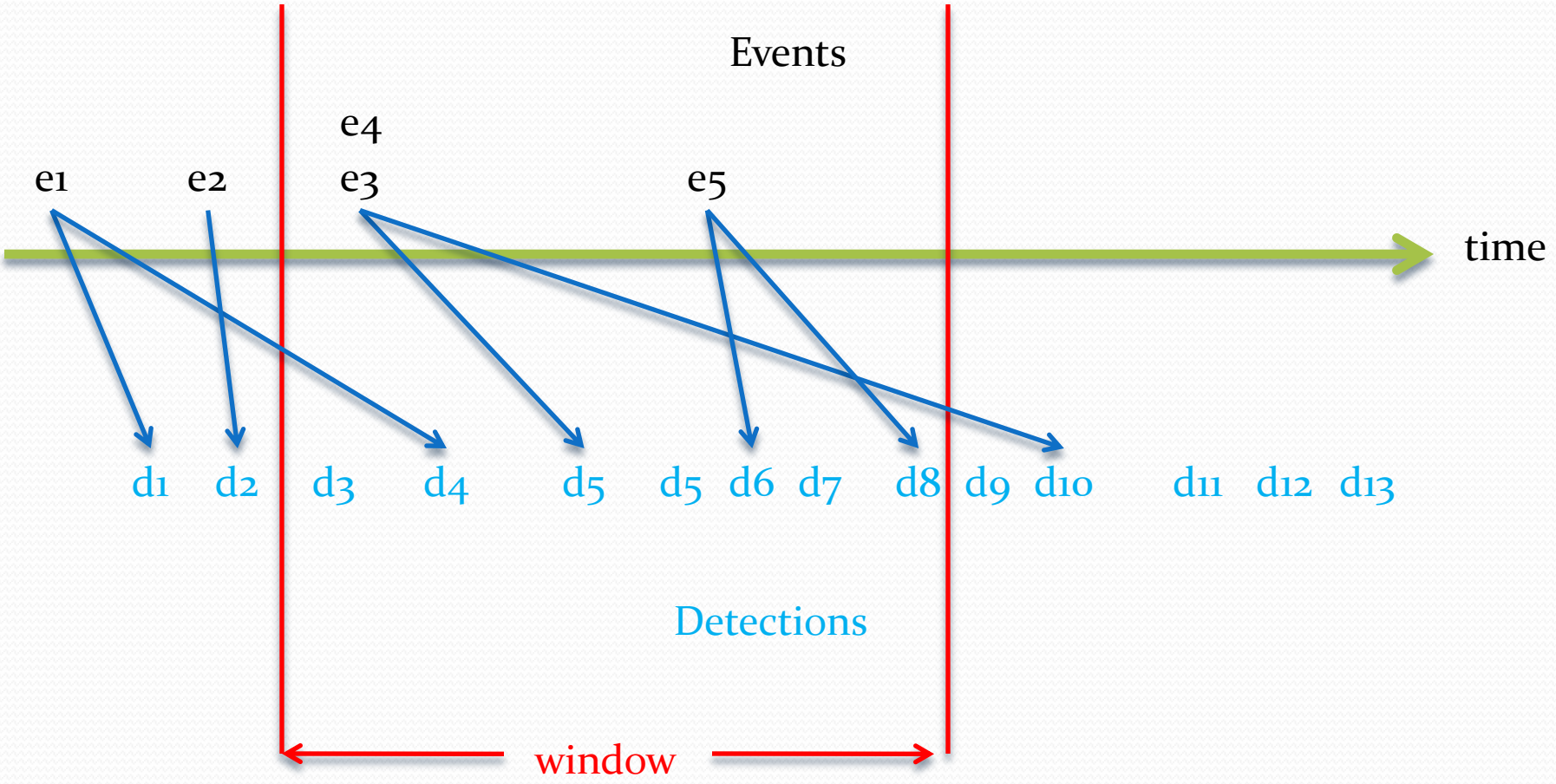
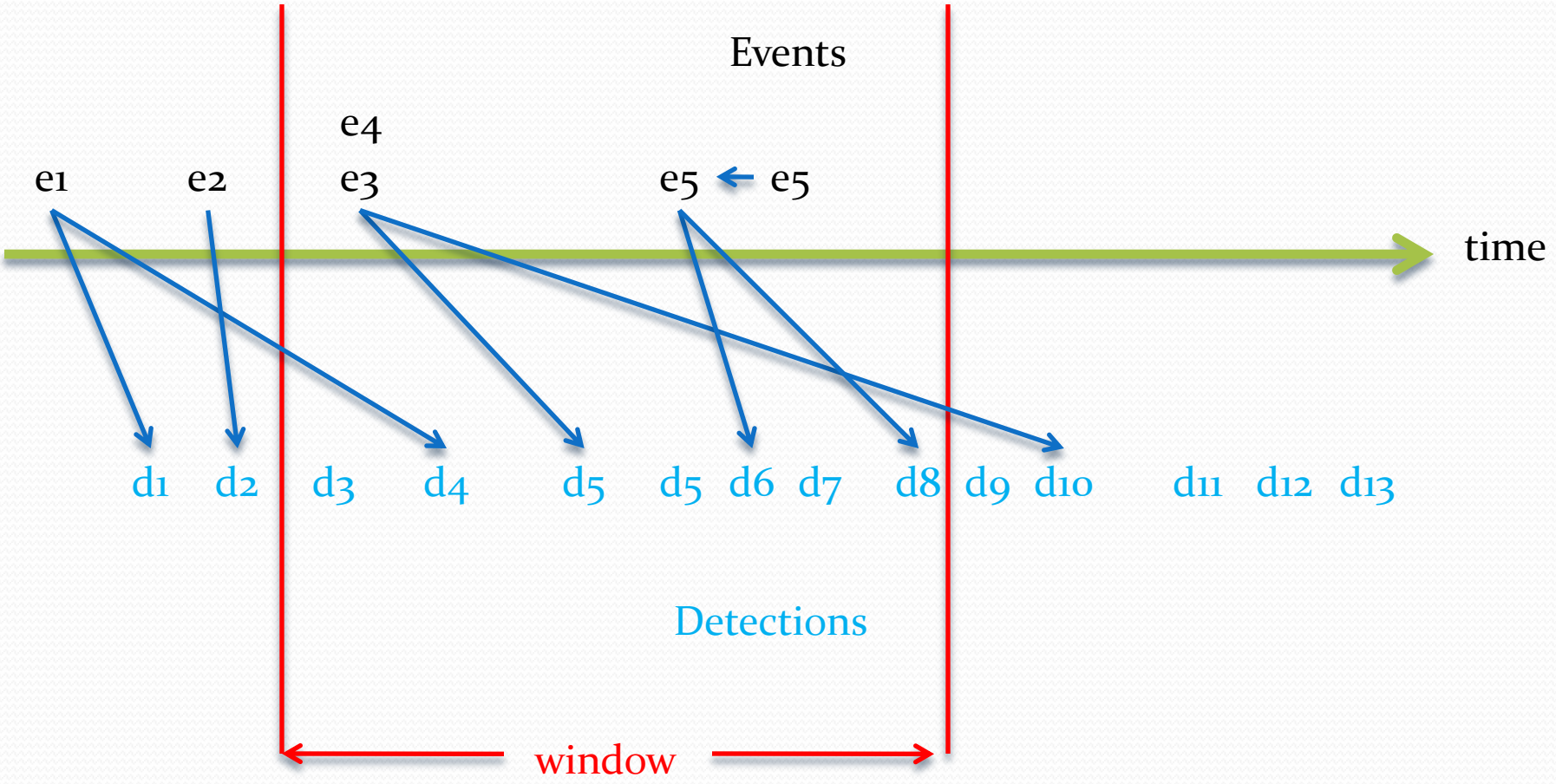
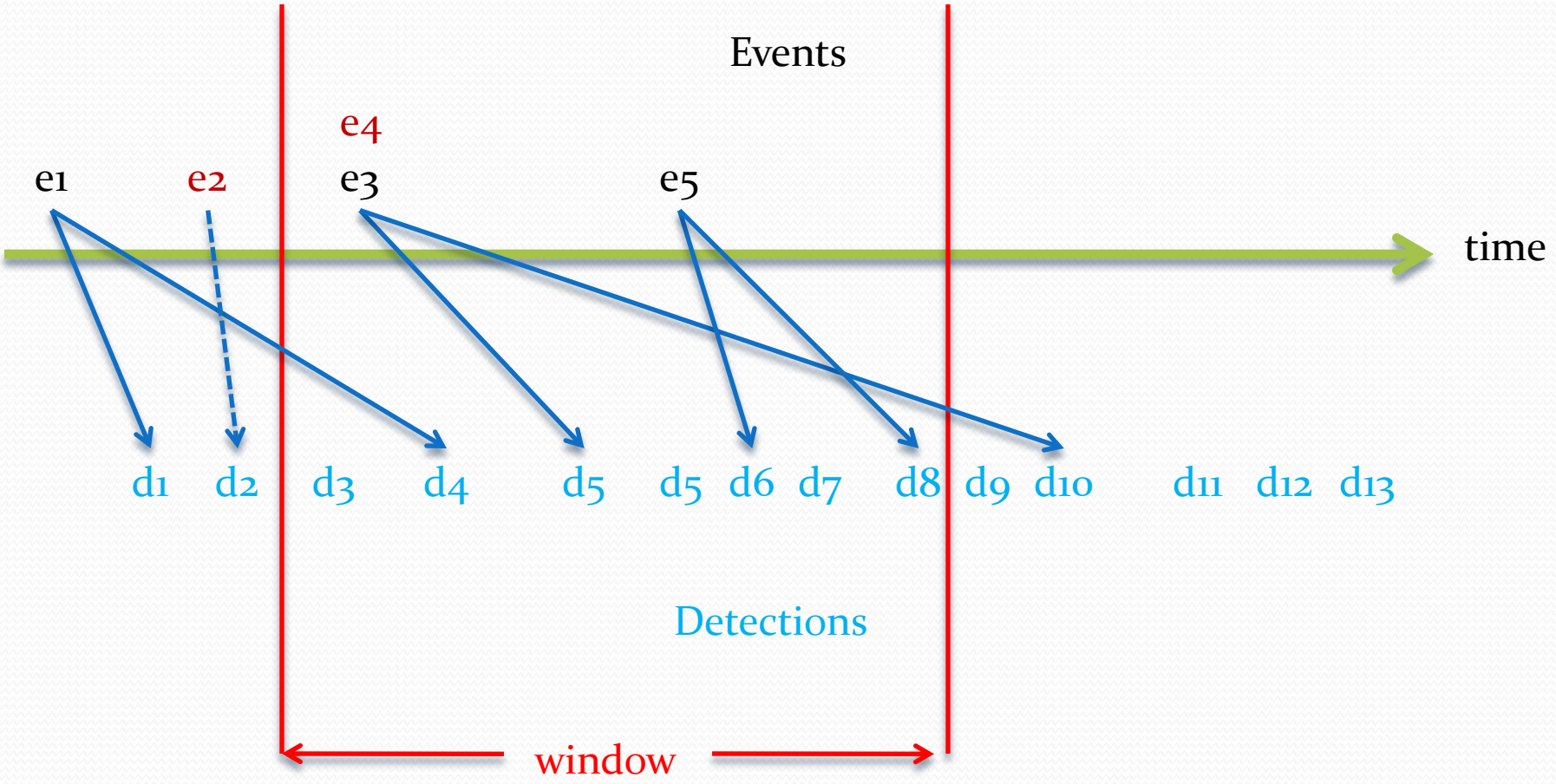


Inference : Relocate Events



Inference : Death Move



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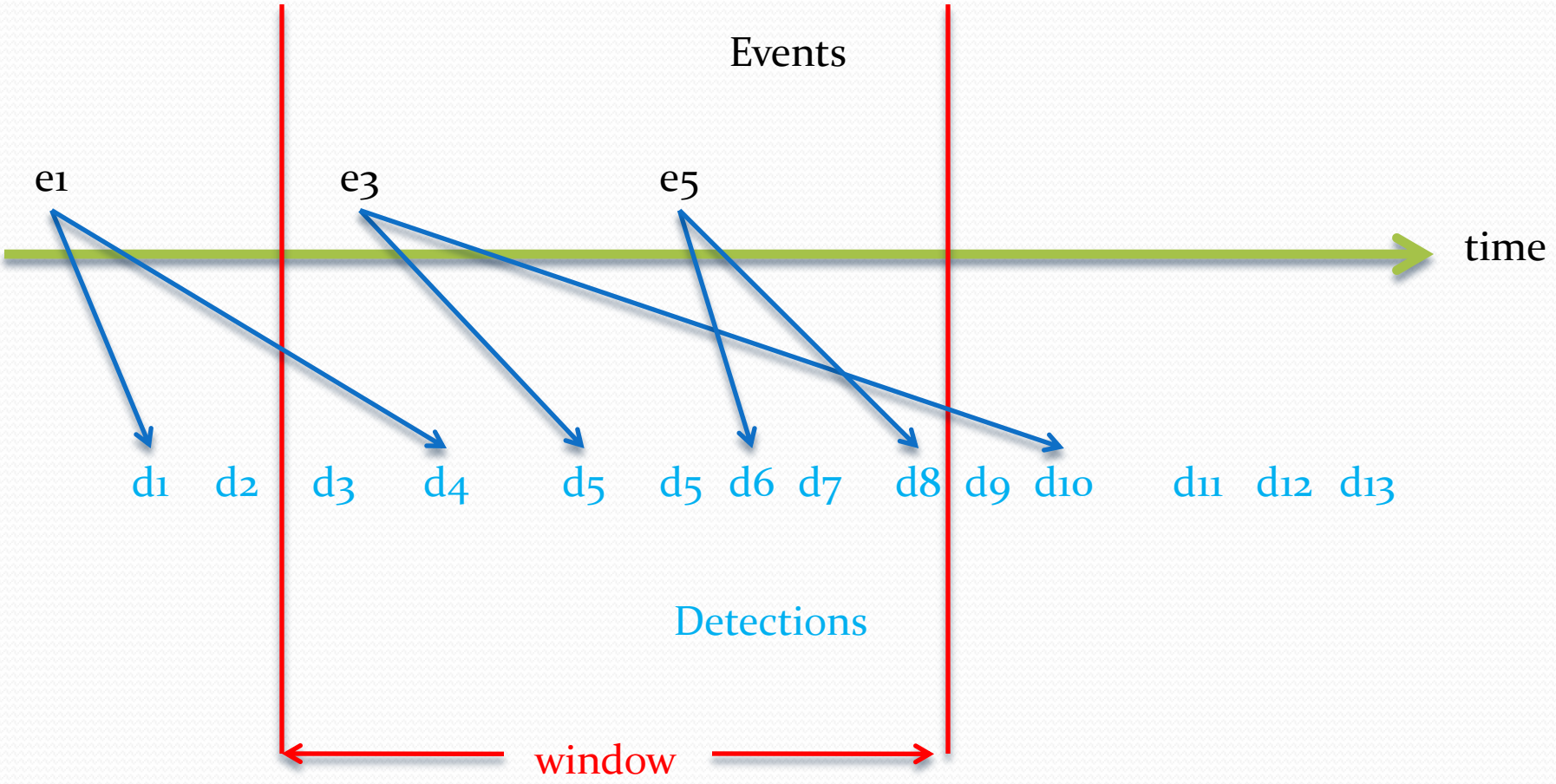
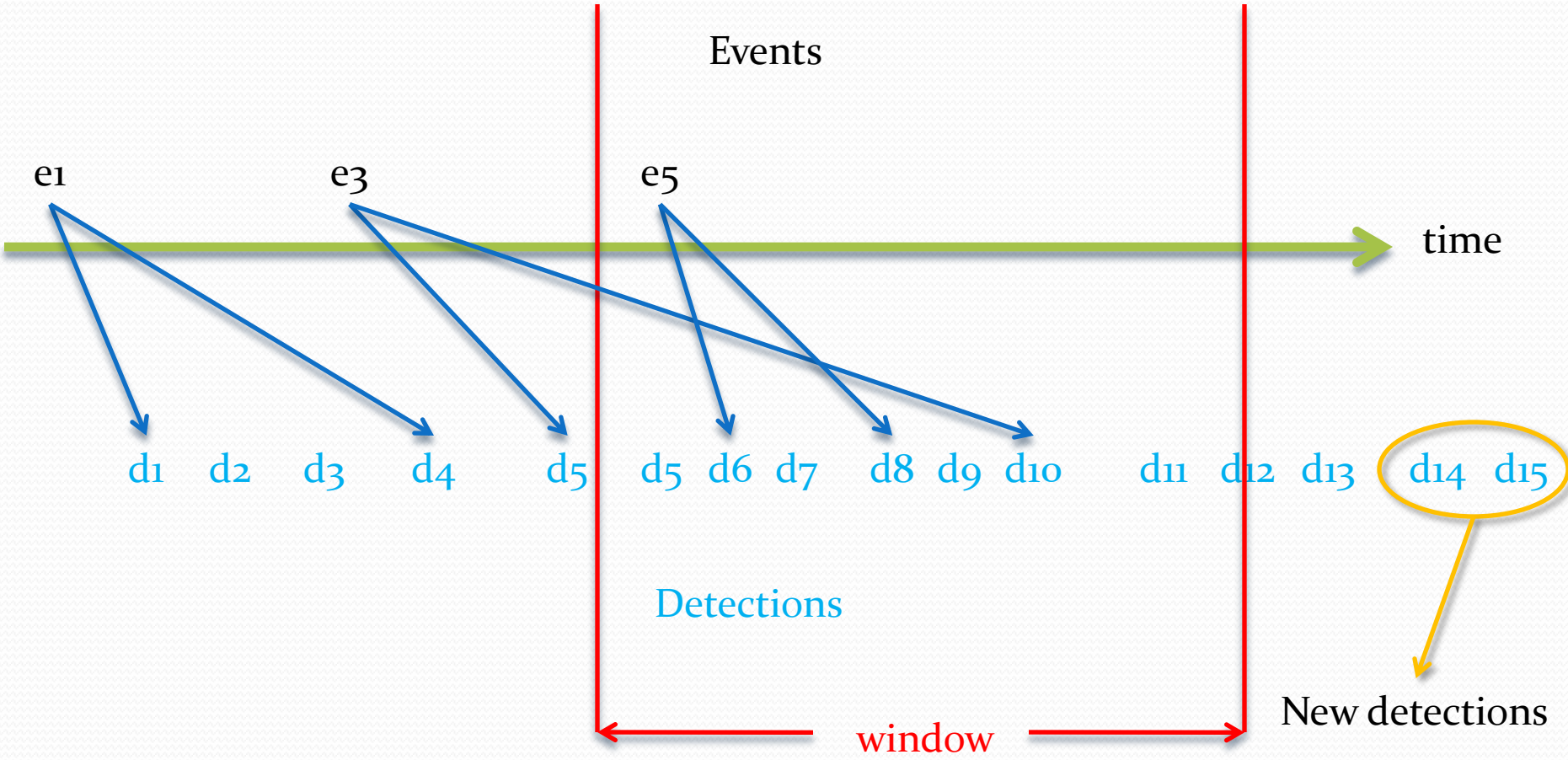
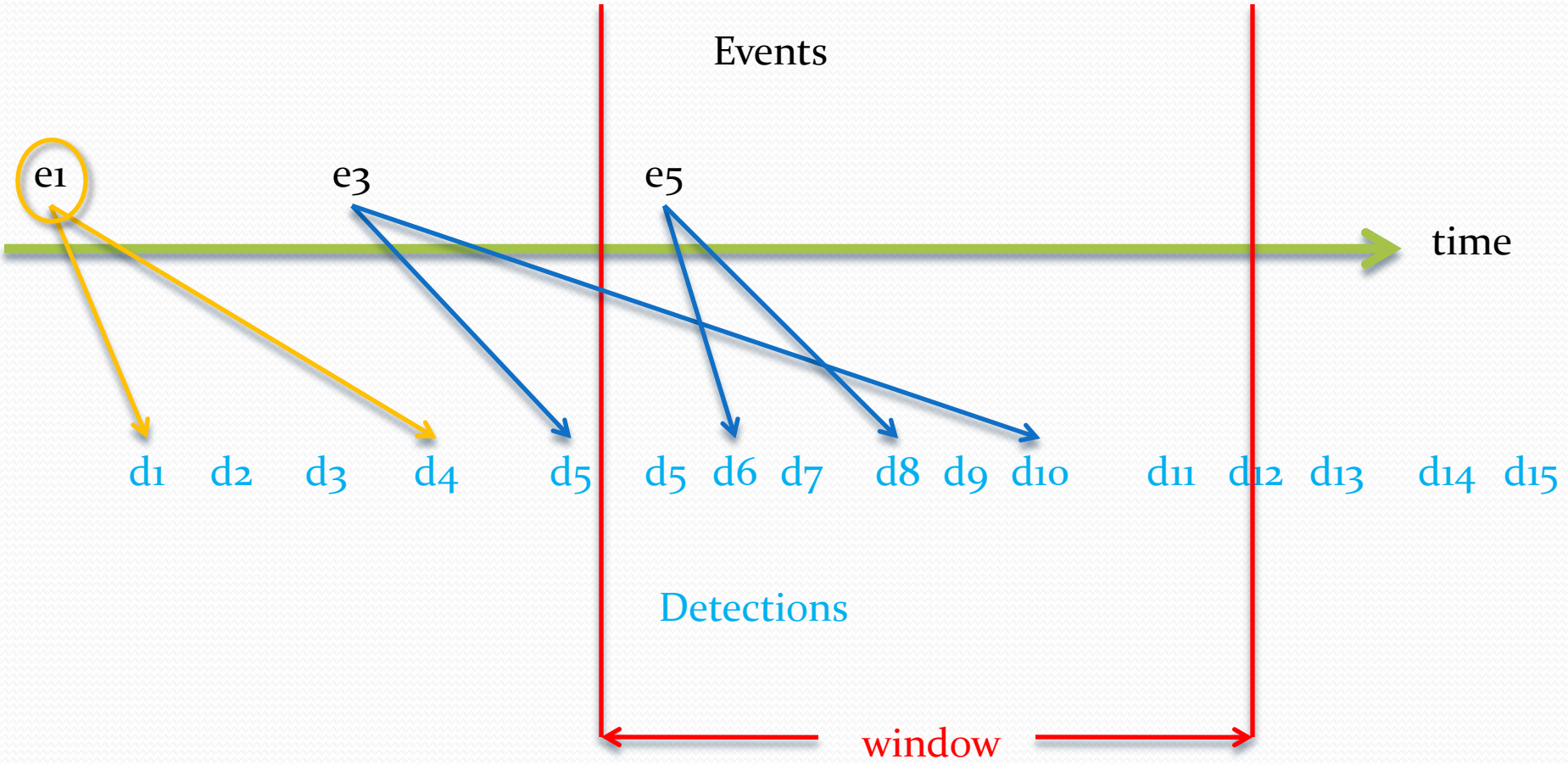


Inference : Move Window Forward



Inference : Output stable events



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Analyzing Performance

- **Min-cost max-cardinality matching** where edges exist between prediction and ground truth events within 50 seconds and 5 degrees.
- The cost of an edge is the distance between the events.
- Precision – percentage of predictions that match.
- Recall – percentage of ground truths that match.
- Error – average distance between matching events.

Recall & Error by m_b

m_b	#events	Recall		Error (km)	
		SEL3		SEL3	
			NET-VISA		NET-VISA
0 – 2	74	64.9		101	
			86.5		93
2 – 3	36	50.0		186	
			75.0		138
3 – 4	558	66.5		104	
			83.5		119
> 4	164	86.6		70	
			89.6		80
all	**832**	**69.7**		**99**	
			84.6		**109**

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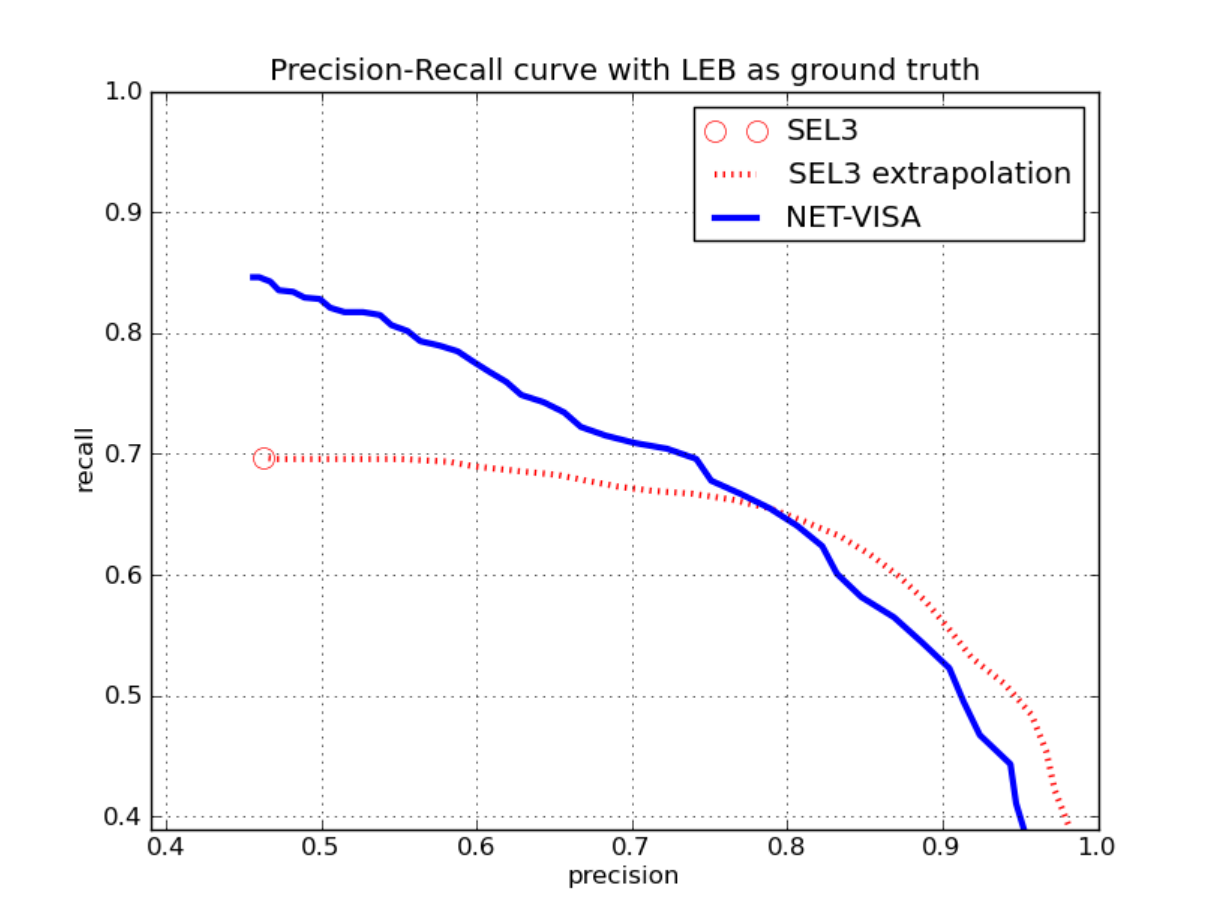
Precision & Recall



SEL3 extrapolation courtesy Mackey & Kleiner

Alternate Evaluation Criteria

Criteria	Precision		Recall		Error (km)	
	SEL3	NETVISA	SEL3	NETVISA	SEL3	NETVISA
Matching, 5 deg, 50s	46.2	45.6	69.7	84.6	99	109
5deg, 50s	48.0	53.4	70.0	85.2	98	104
250km,40s	41.5	46.2	60.9	74.9	63	71

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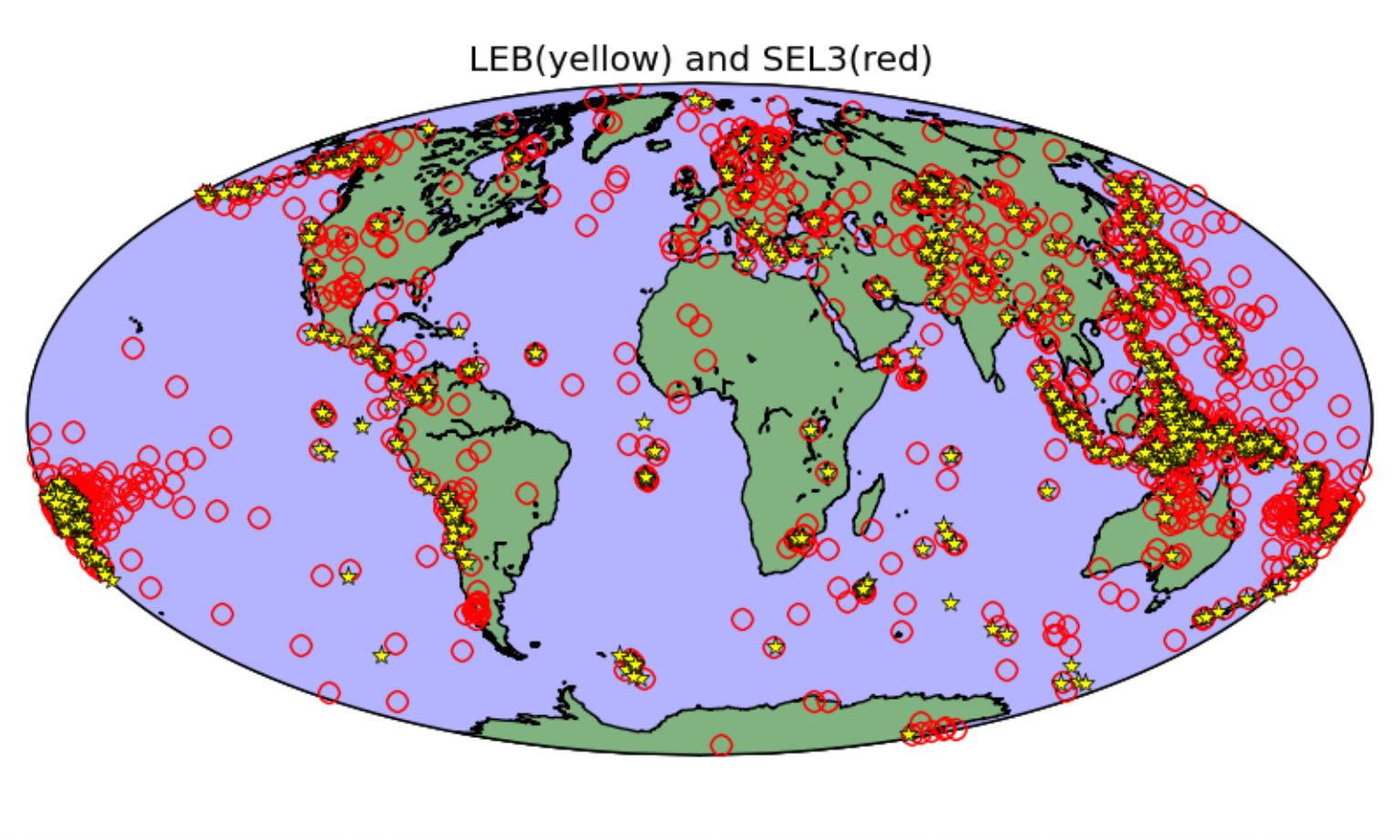
All Predicted Events (LEB & SEL3)



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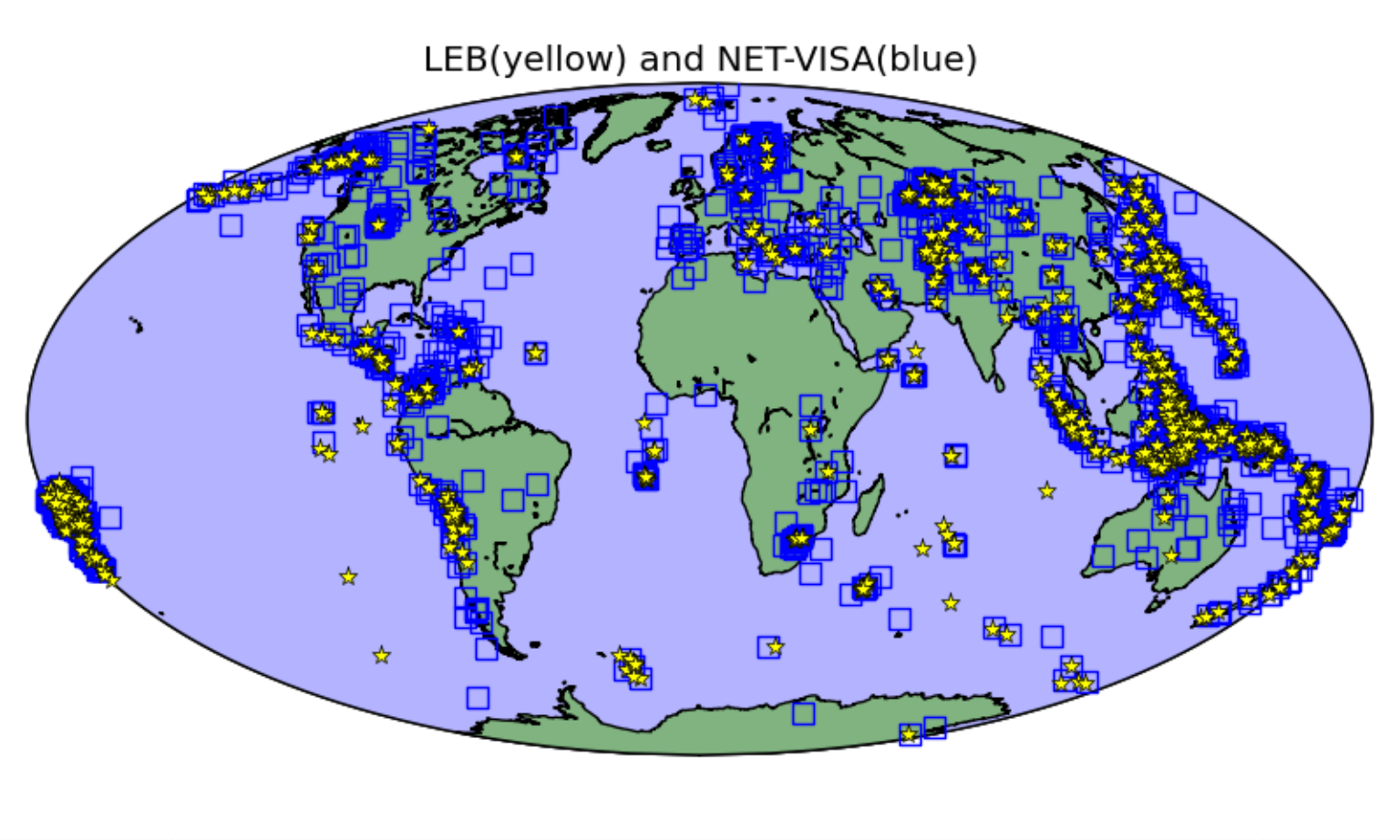


Error Analysis : 1

- NET-VISA considers many more combinations of detections than LEB
  - => Event locations tend to be different
  - => New events are predicted

Additional Detections in NET-VISA

m_b	#events	#Additional detections
0 – 2	64	2
2 – 3	27	2
3 – 4	465	2
>4	148	4
All	704	3

Example 1 :

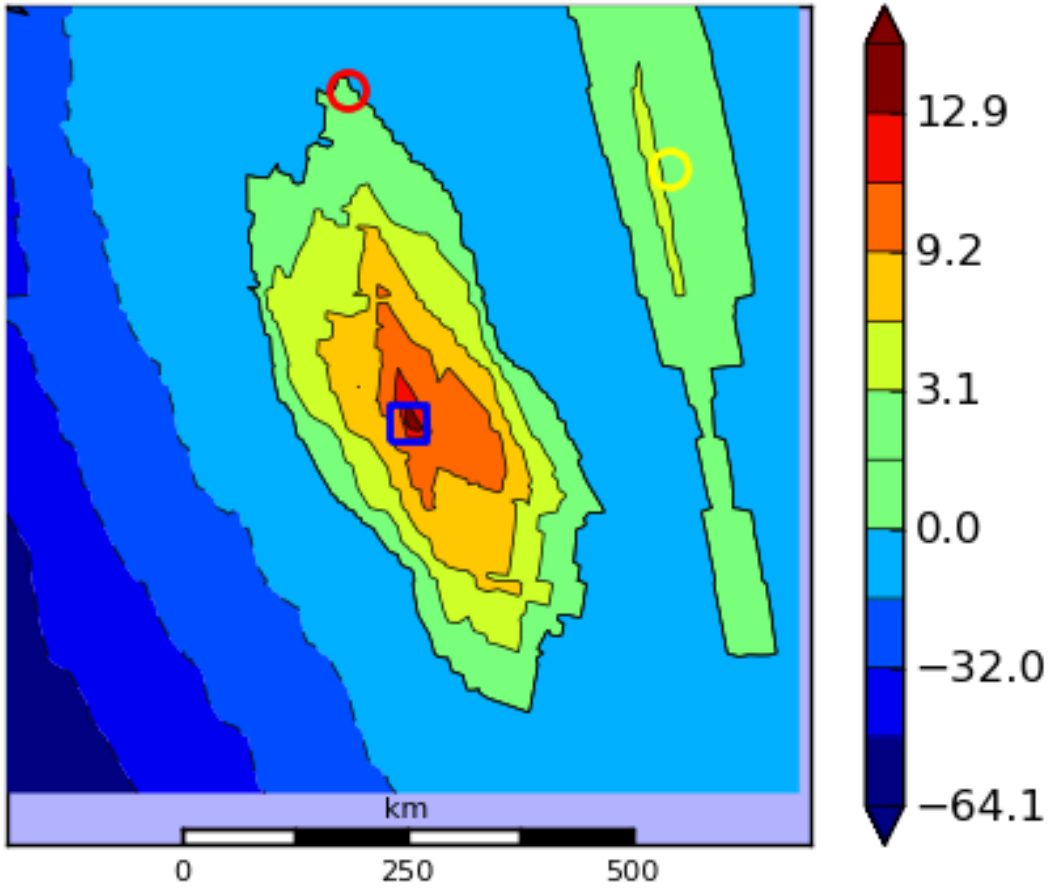
Orid	Phase	Sta	Timeres	Azres	Slores
5295573	P	ASAR	-1.9	-8.5	-0.2
5295573	P	WRA	-0.8	-2.2	0.6
5295573	P	FITZ	1.2	10.2	-0.7
5295573	P	CTA	1.6	-16	-0.3

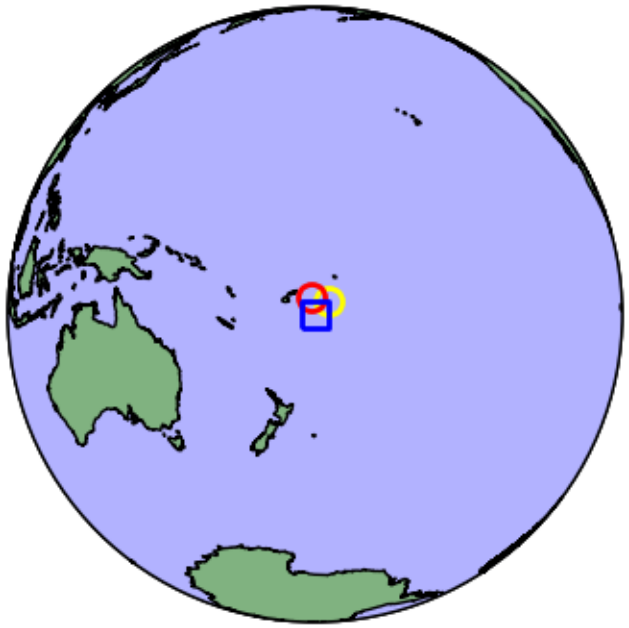
LEB

Runid	Orid	Phase	Sta	Timeres	Azres	Slores
8	11	P	ASAR	0.6	-10.8	-3
8	11	P	WRA	0.4	-4.8	0.6
8	11	P	FITZ	6.8	-47.1	-1.3
8	11	P	TXAR	3.3	-84.9	0.9
8	11	P	AFI	-1.1	22.0	-2.4
8	11	P	RPZ	0.6	24.6	12.8

NET-VISA

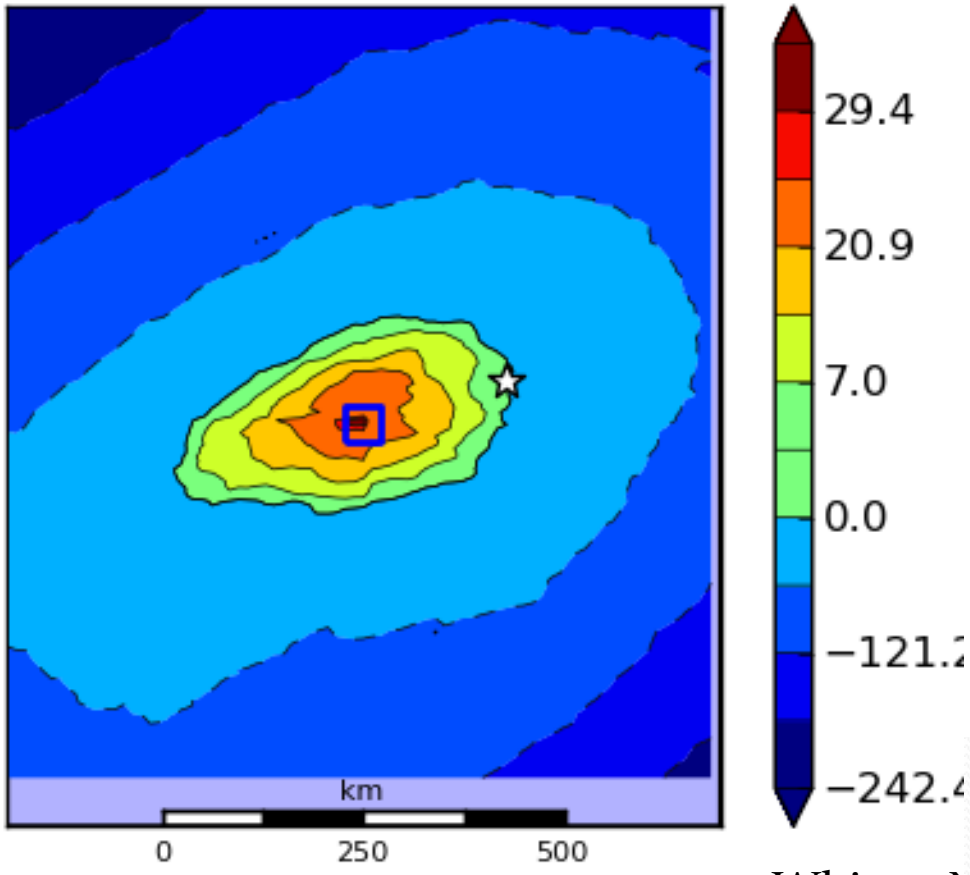
Example 1: Posterior Probability

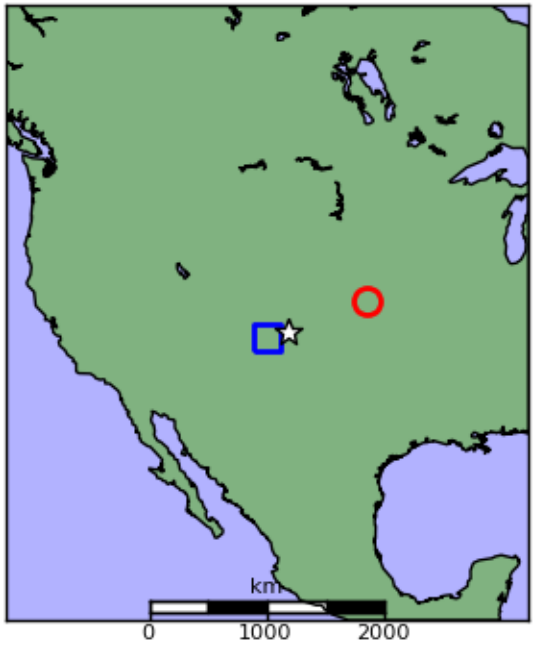




Blue – NET-VISA, Yellow – LEB, Red – SEL3

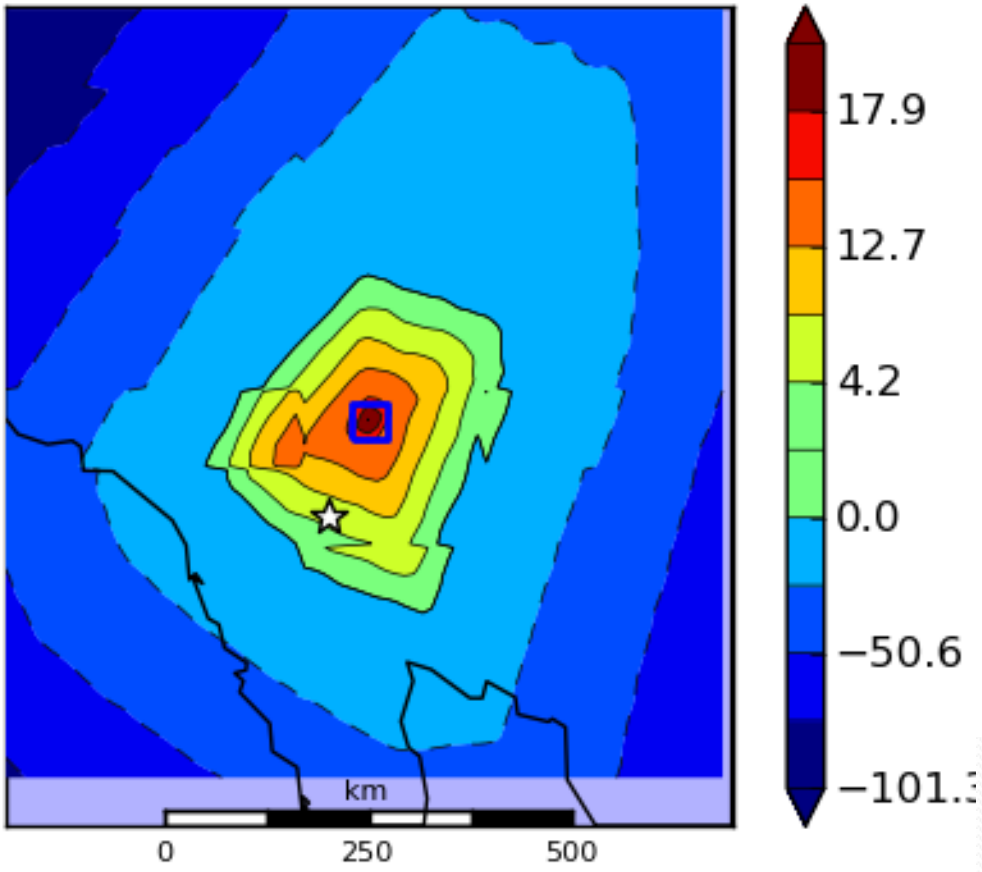
Ex 2: NEIC Event (ML 3) missed by LEB





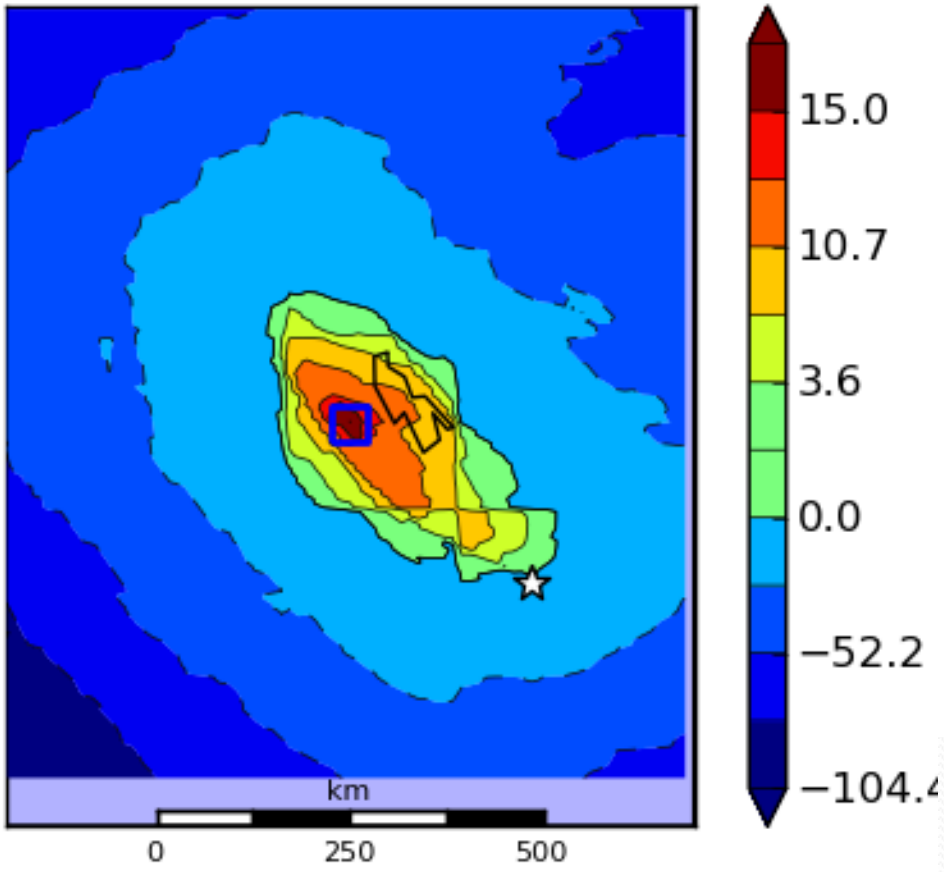
White – NEIC, Blue – NET-VISA, Red – SEL3

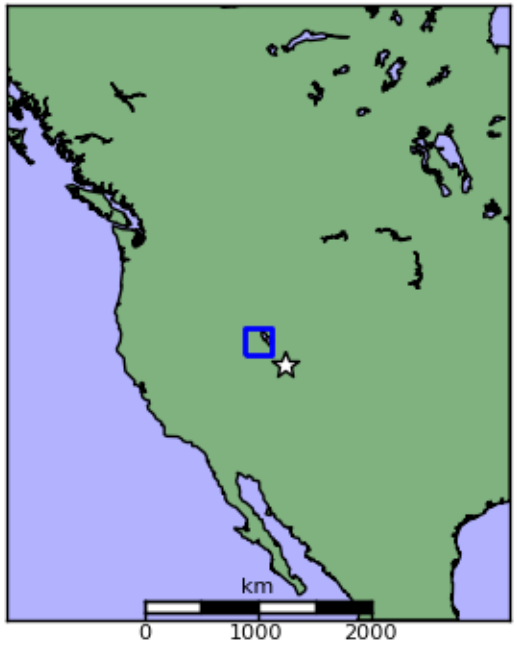
Ex 3: NEIC Event (ML 3.7) missed by LEB



White Star – NEIC : Courtesy ISC

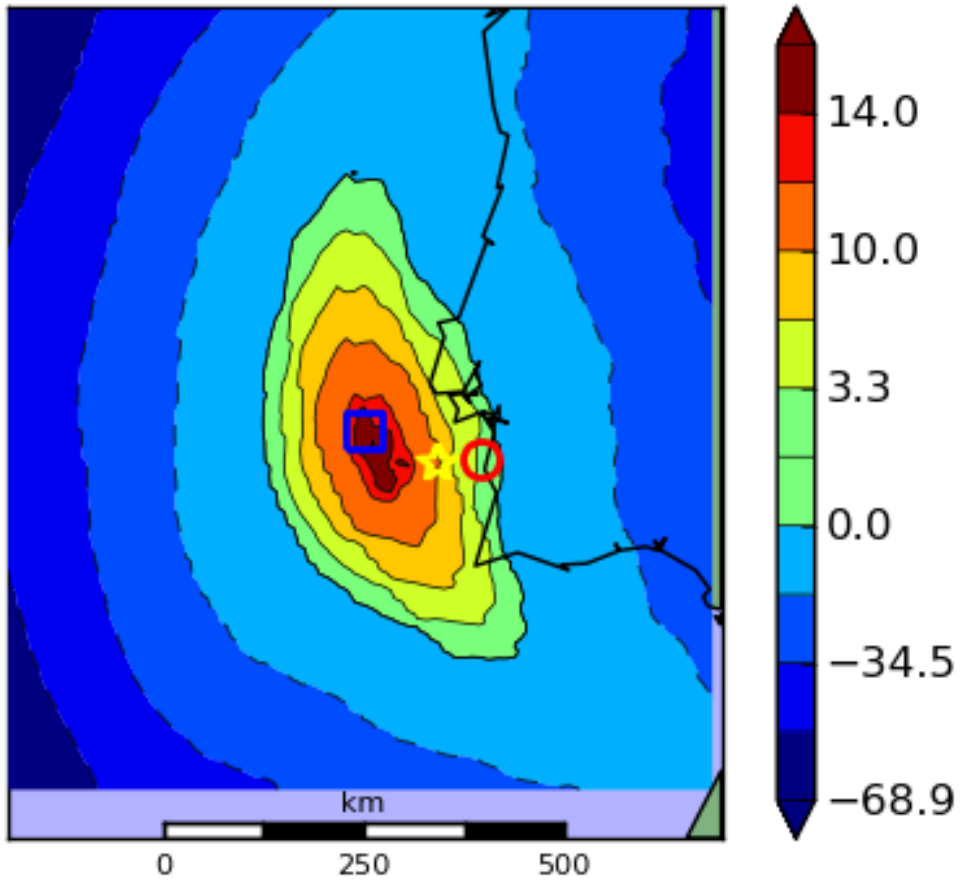
Ex 4: NEIC Event (ML 2.6) missed by LEB

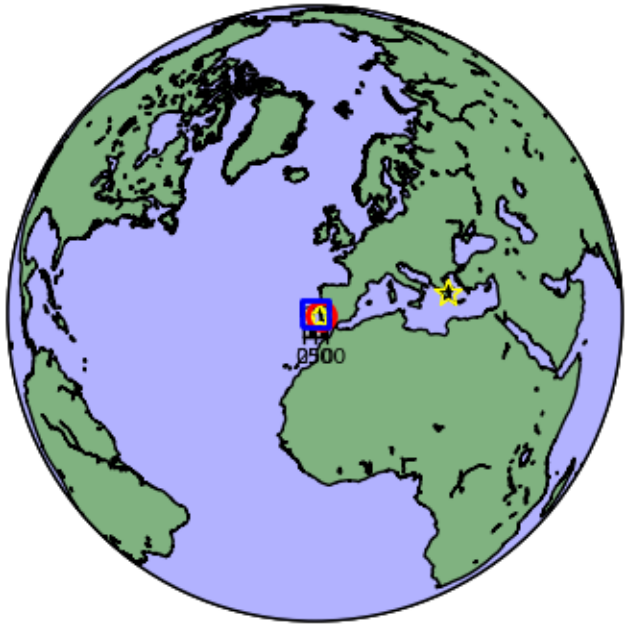




White Star – NEIC : Courtesy ISC

Ex 5: Portugal Event missed by LEB



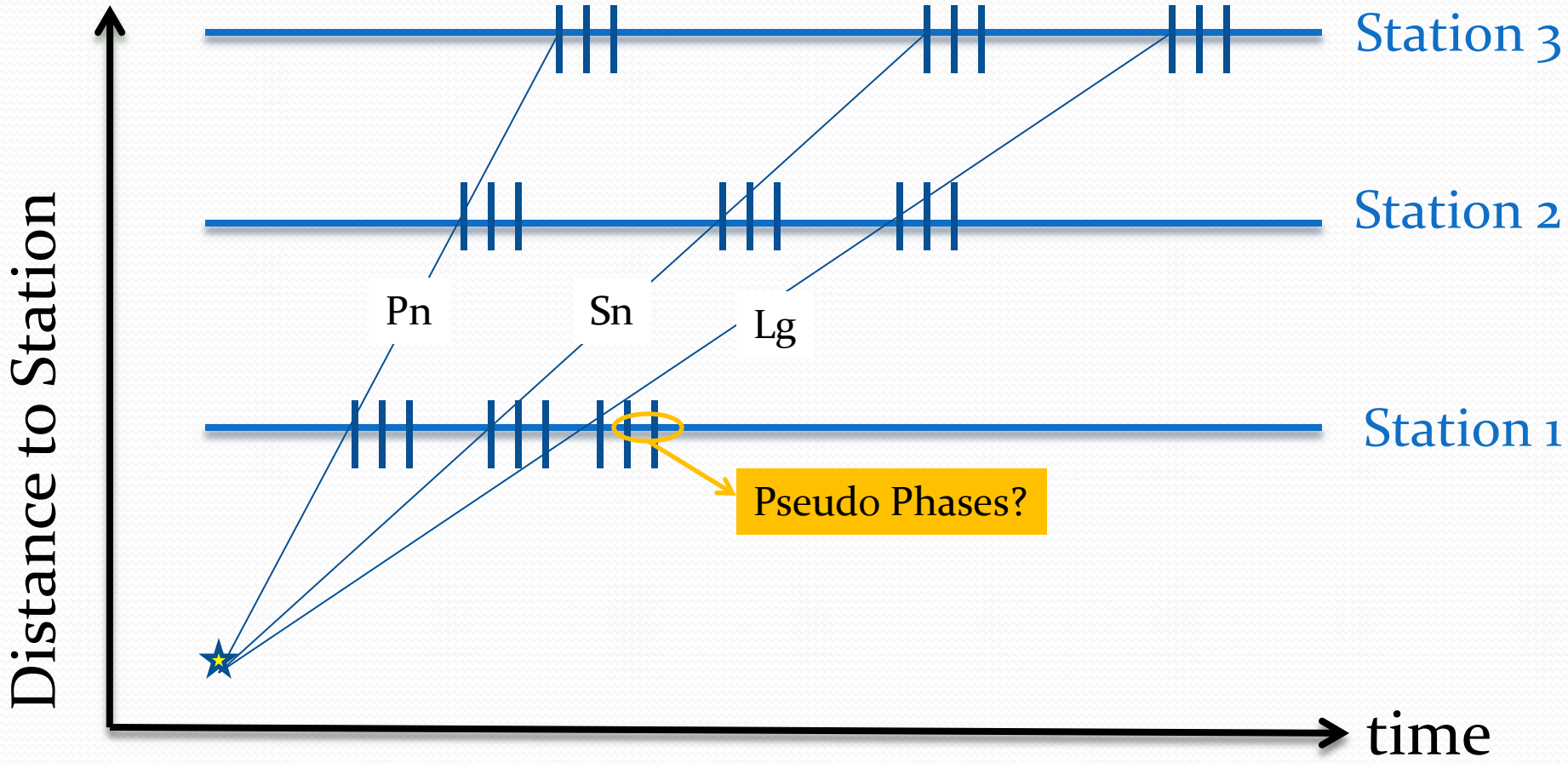


Yellow star – LDG (French) network: Courtesy ISC

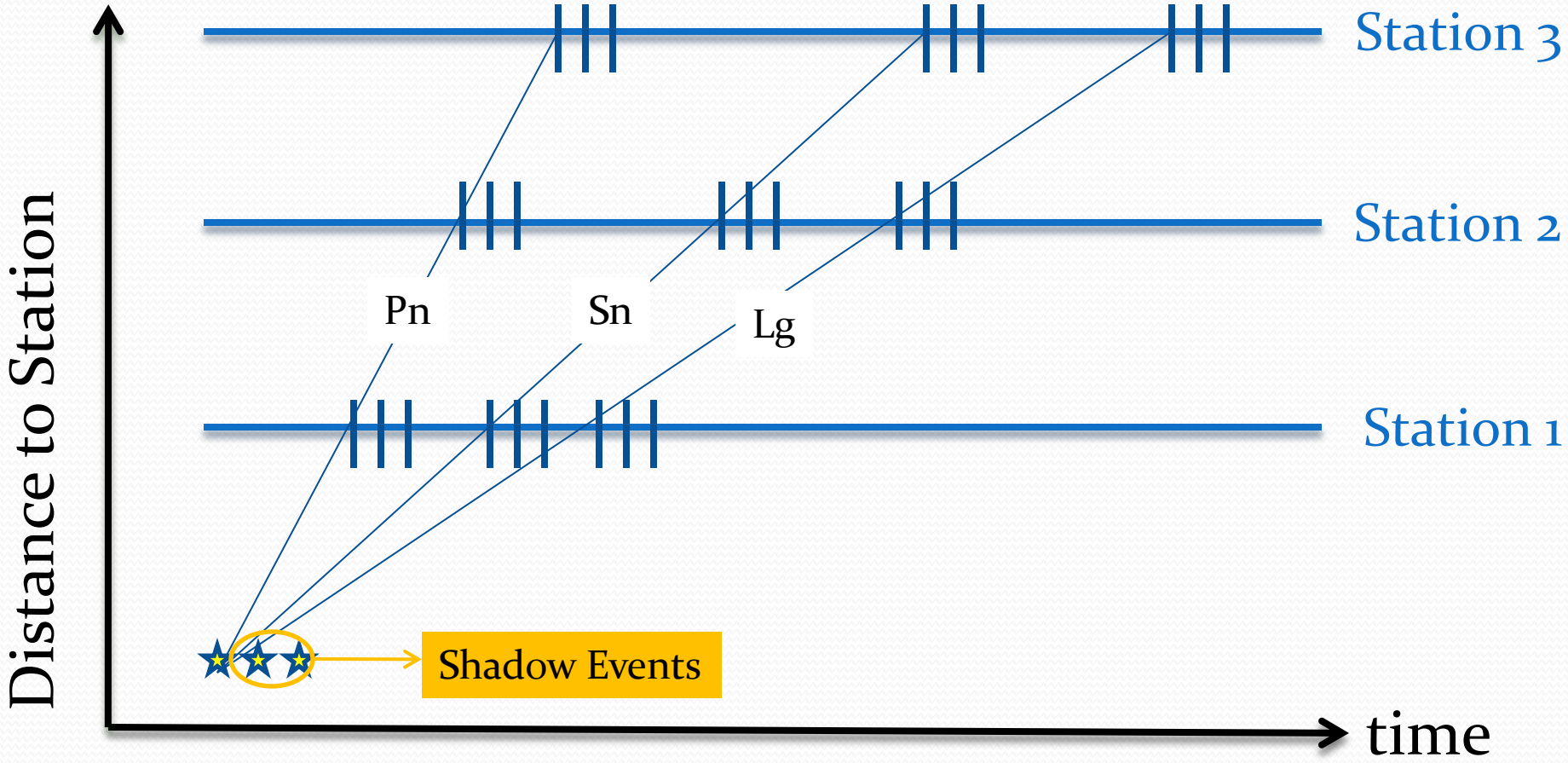
Error Analysis : 2

- A single phase may produce more than one detection
- When this occurs consistently across multiple stations NET-VISA hypothesizes multiple events

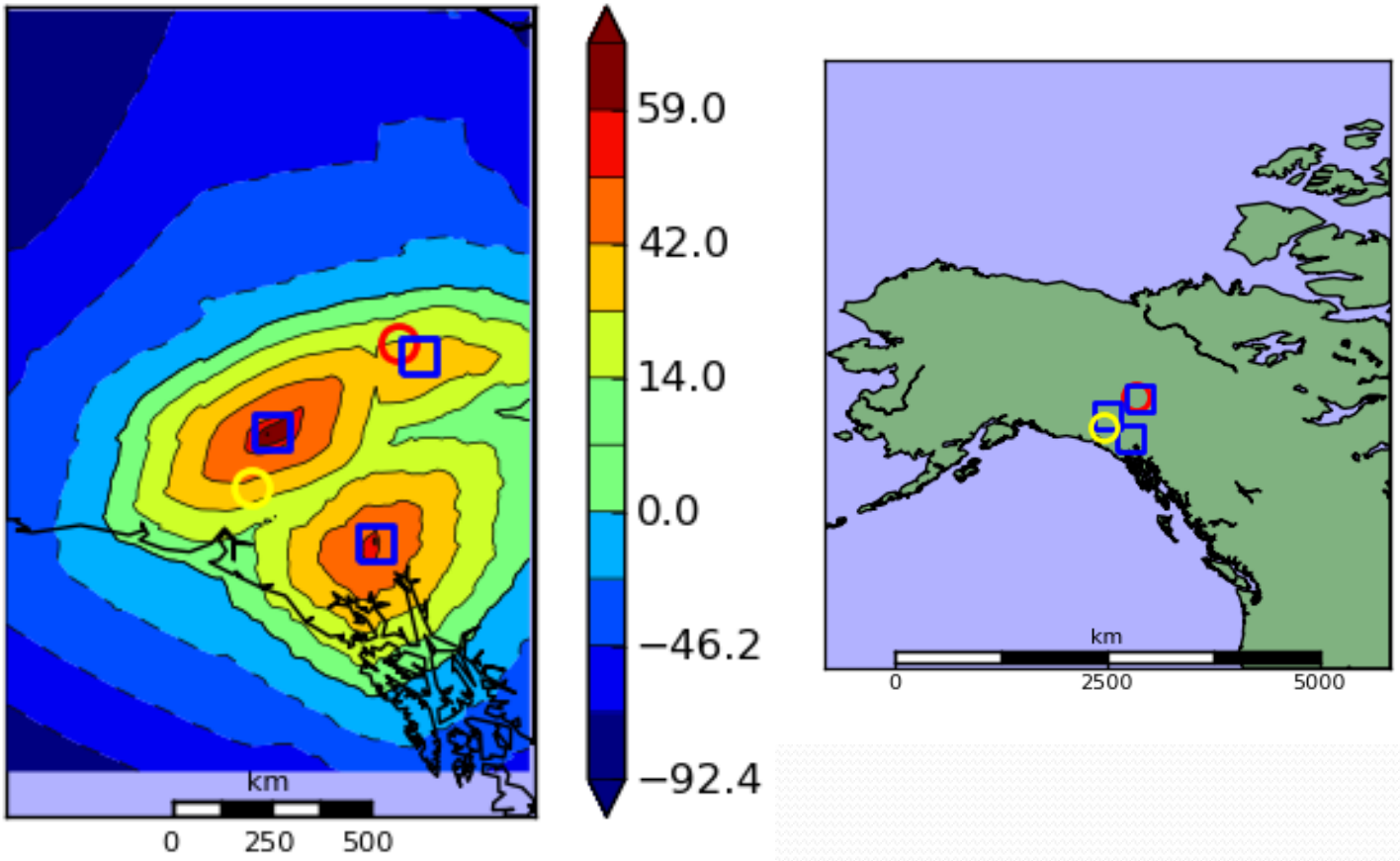
Error Analysis : Pseudo Phases



Error Analysis : Shadow Events

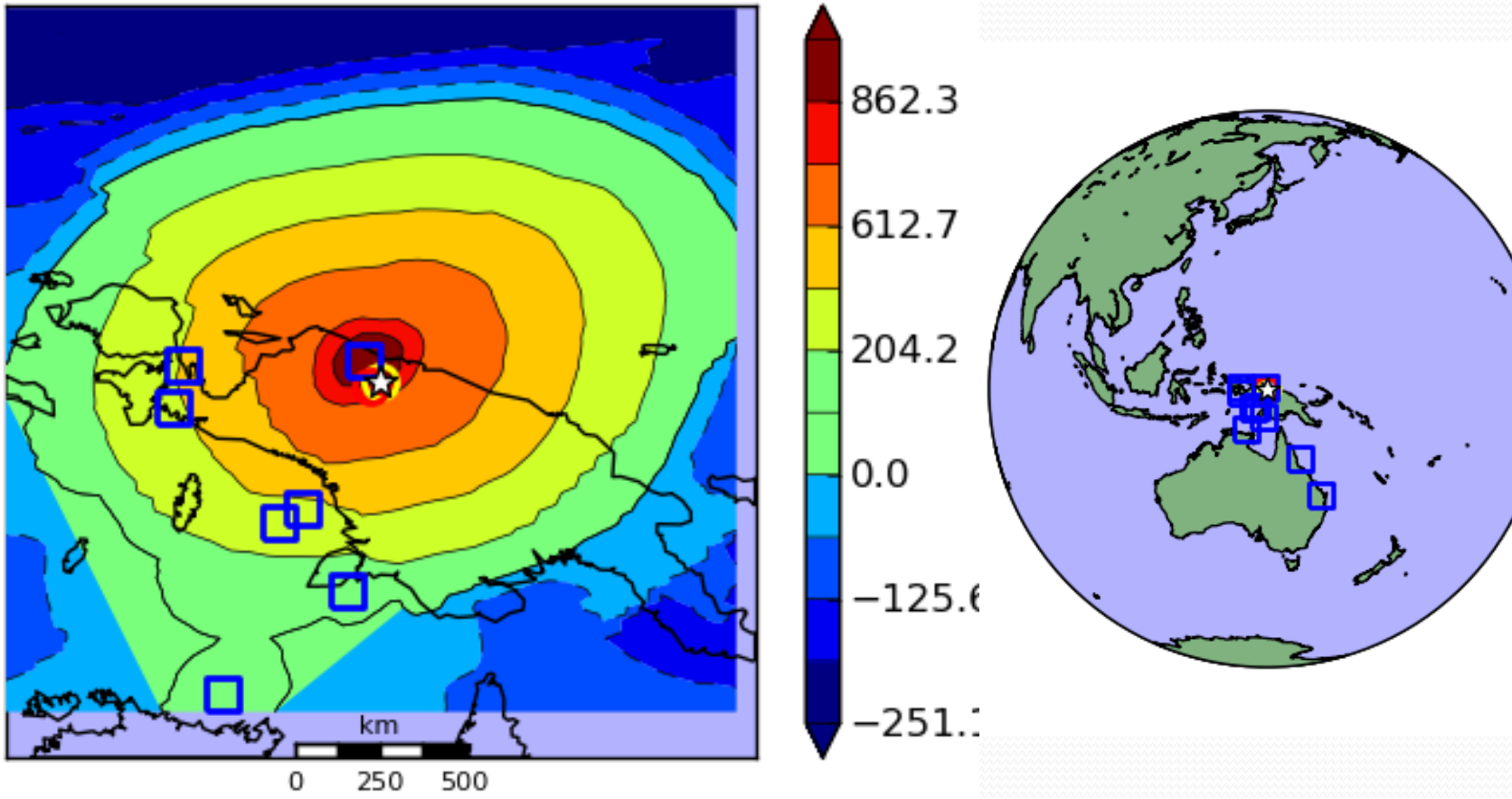


Ex 6: Shadow Events (LEB ML 2.9)

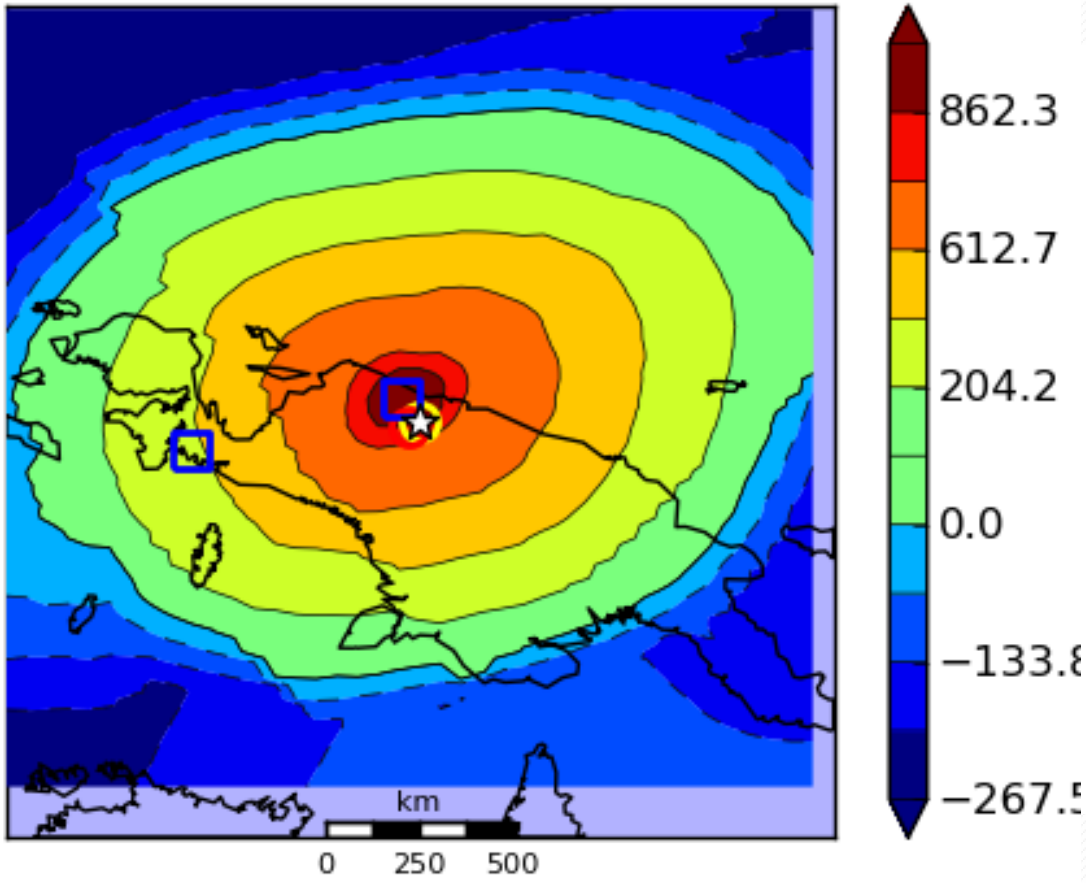


Blue – NET-VISA, Yellow – LEB, Red – SEL3

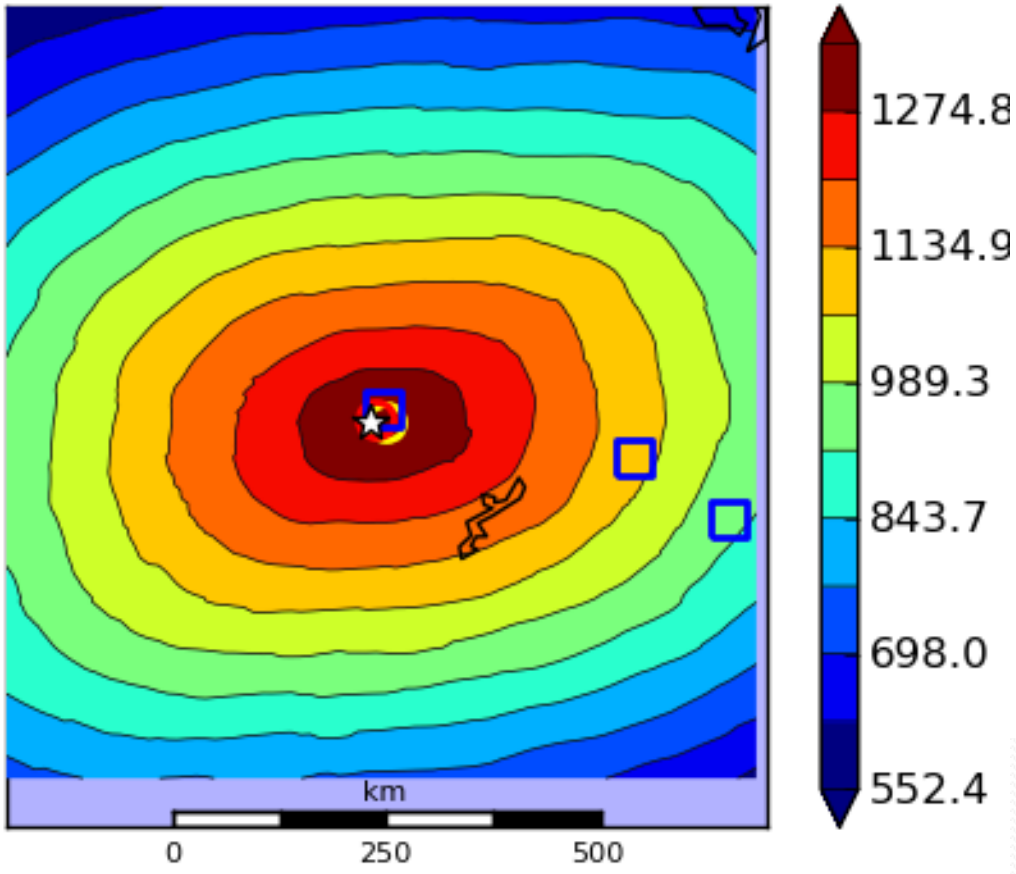
Ex 7: Shadow Events (m_b 5.7)

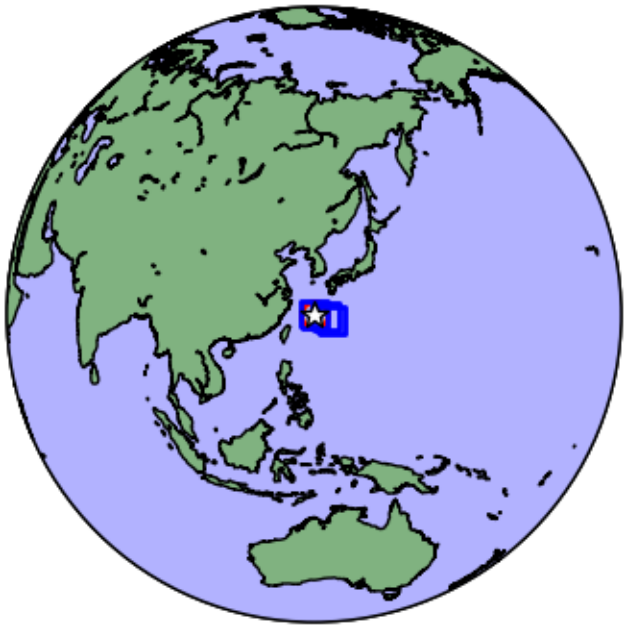


Hack … Suppress Duplicates

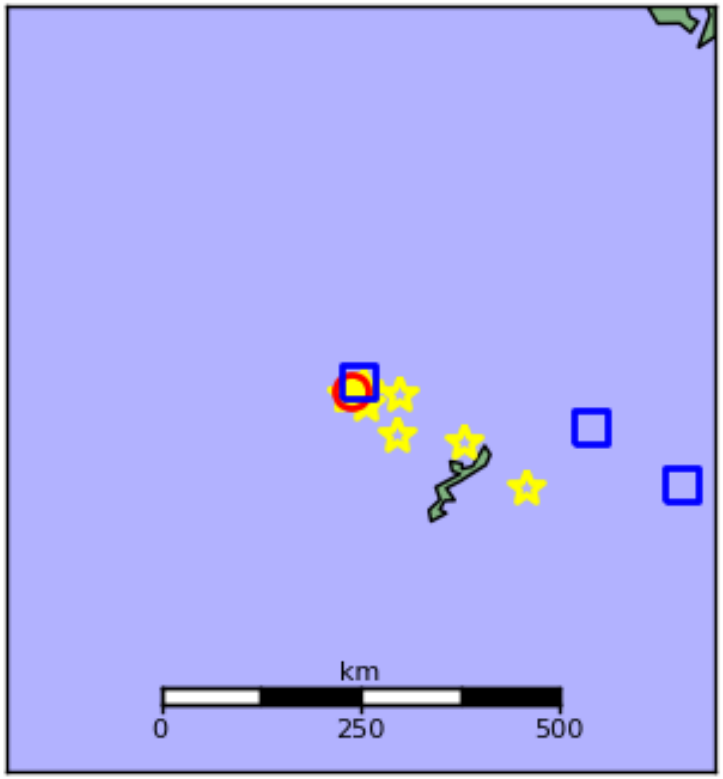


Are these duplicates?





ISC event location from all sources

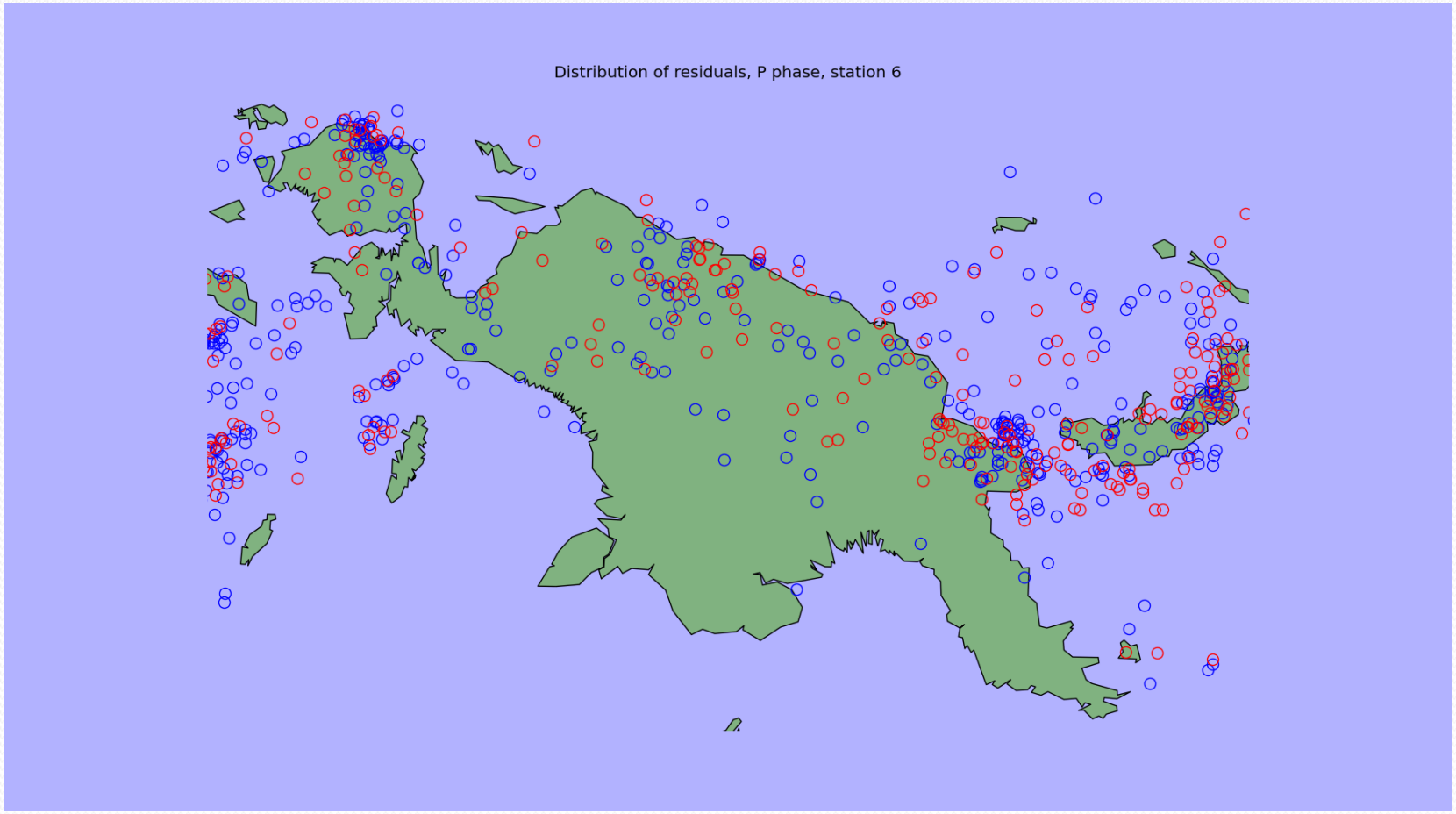


Yellow Stars : various sources for same event : Courtesy ISC

Overview

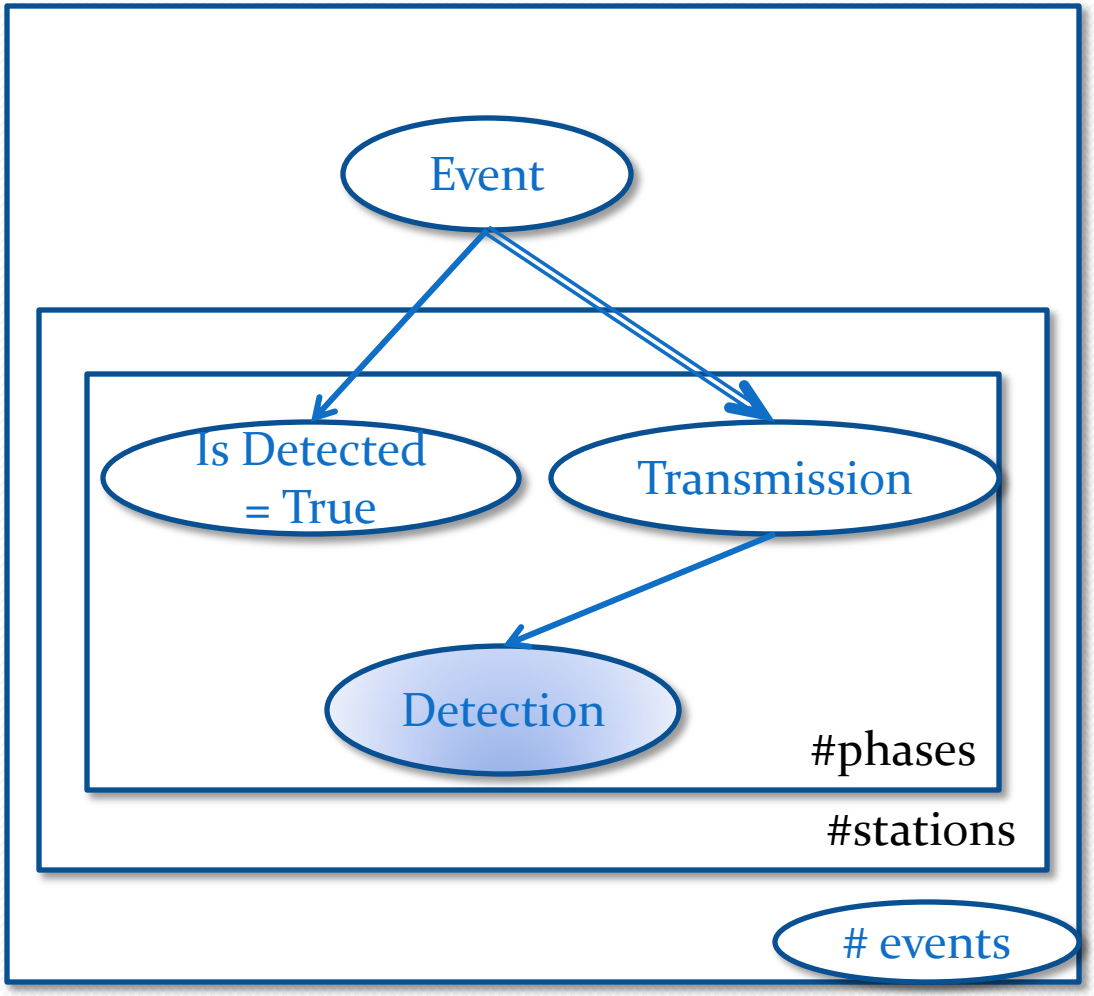
- Generative Probabilistic Model
- Inference
- Results
- Analysis
- Future plans

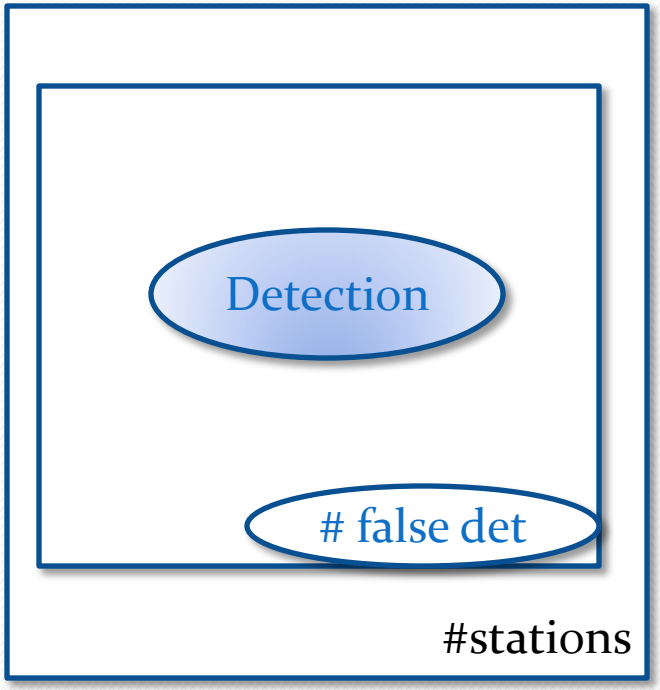
Travel Time Corrections



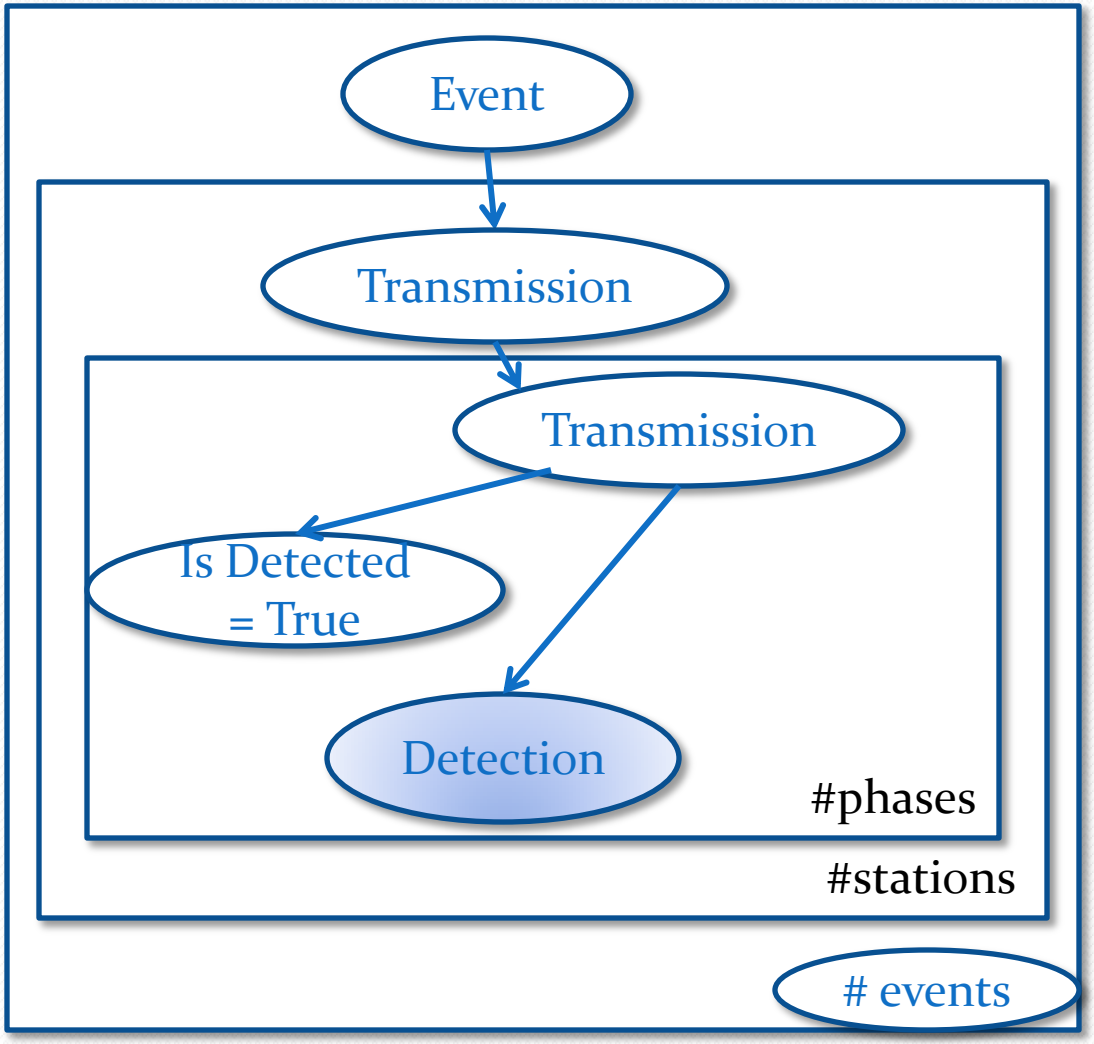
Blue – positive, Red – negative residual

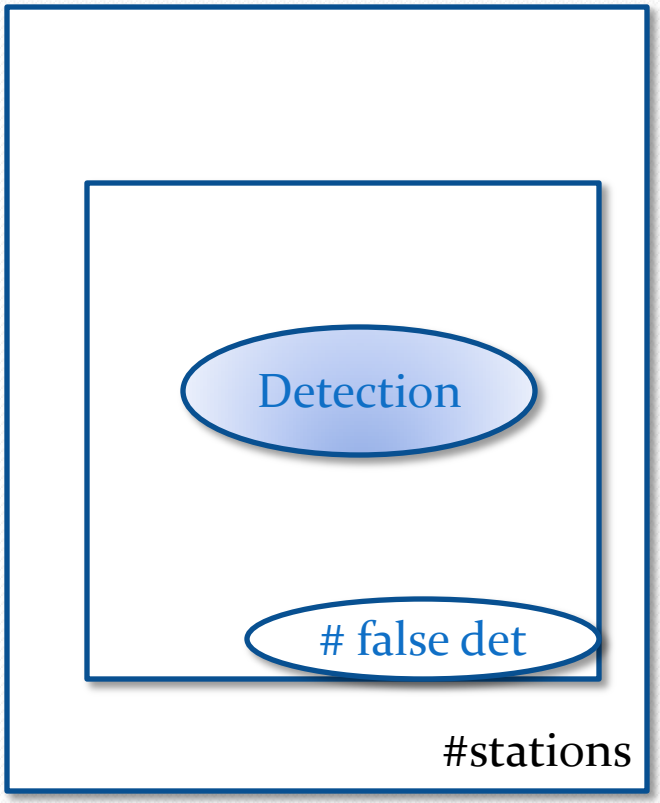
Current Generative Model



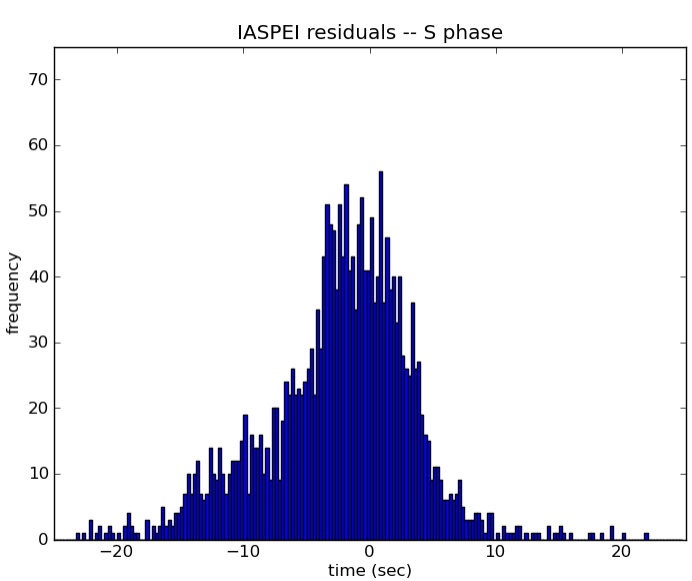


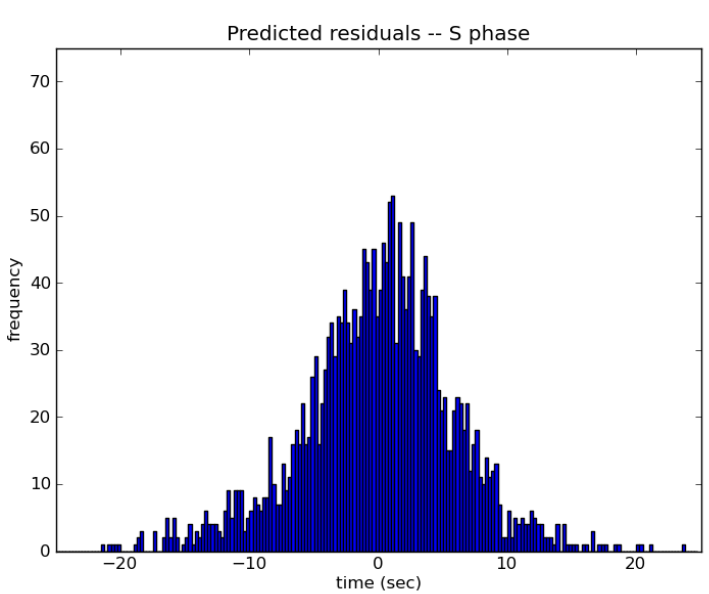
Correlated Phase Detections

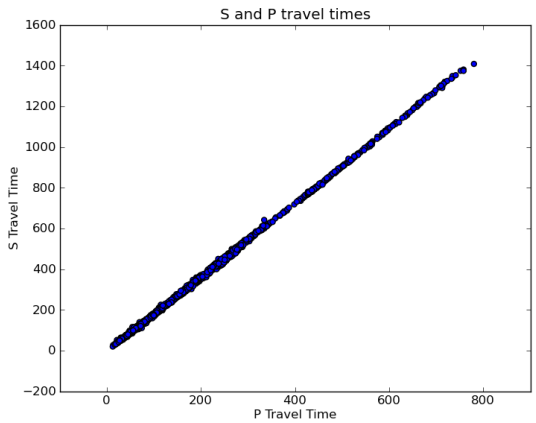




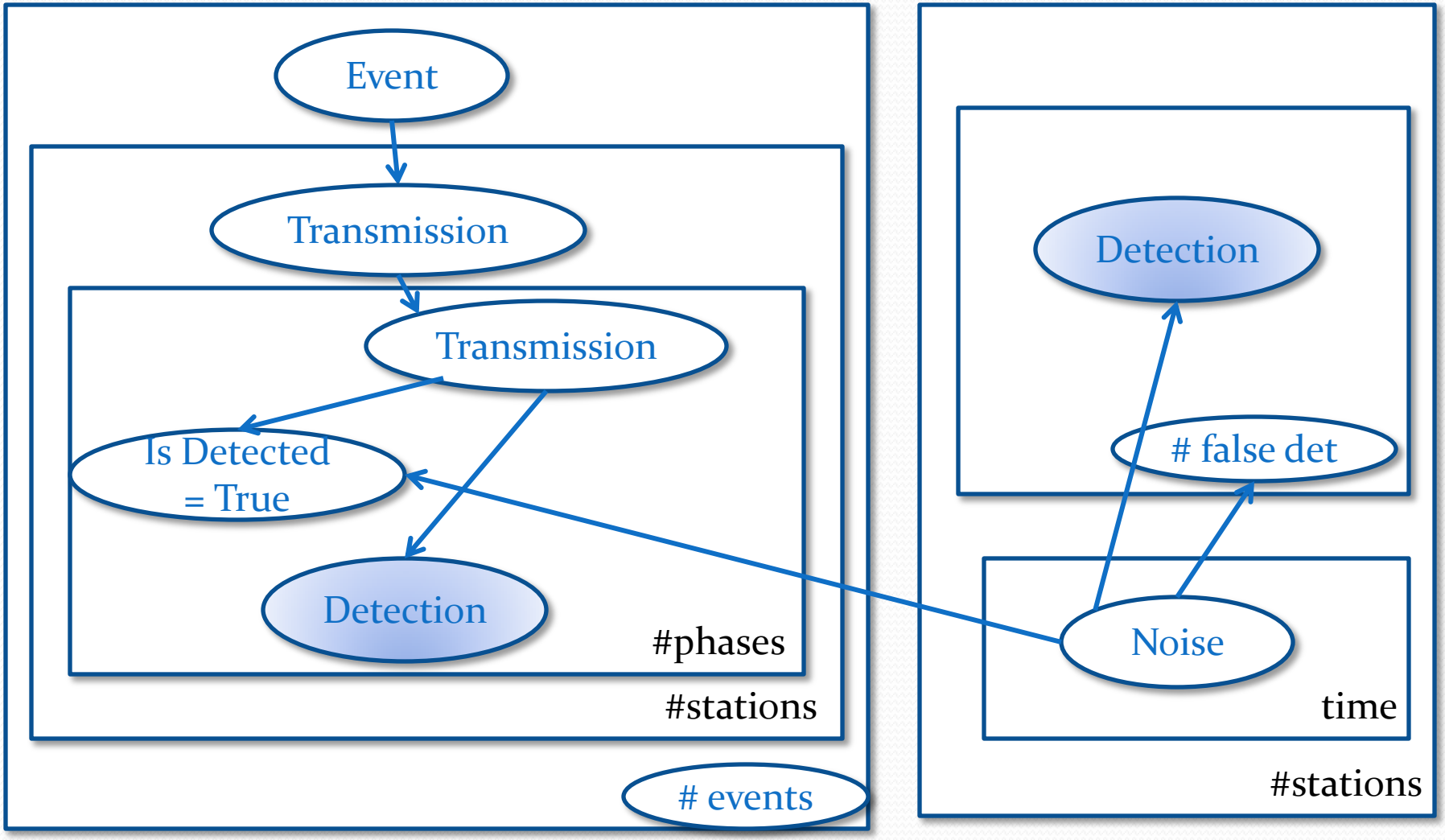
Correlation between S and P travel times







Time Varying Station Noise Affects Detections and False Detections



Others…

- Event location prior using Fisher Binghams etc.
- Model for Hydroacoustic and Infrasound detections
- Multiple detections per phase (pseudo phases)
- IDC Evaluation of NET-VISA
- SIG-VISA

Conclusion

- Generative Probabilistic Model of seismic events, transmission, and detection
- MAP inference for direct comparison with SEL3
- 15% higher recall than SEL3 at the same precision
- Potentially more events than LEB