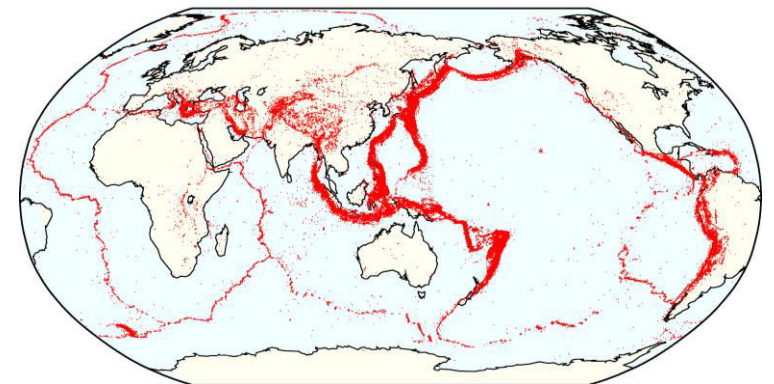
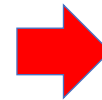
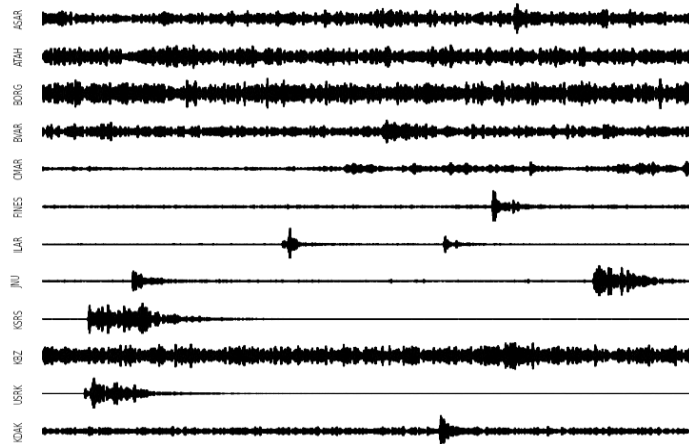


Initial Evaluations of Signal-based Vertically Integrated Seismic Analysis (SIGVISA)

Dave Moore

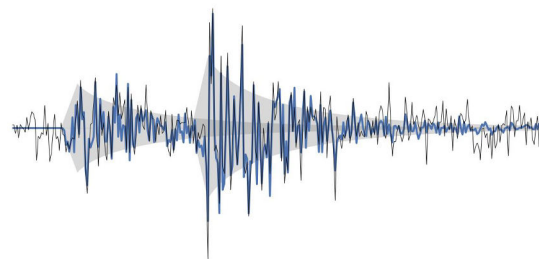
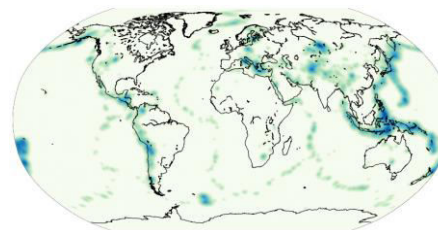
with Stephen Meyers, Kevin Mayeda, Stuart Russell

University of California, Berkeley



Monitoring as Bayesian inference

- $P(\text{events})$ describes **prior probability** over **seismic event histories**
- $P(\text{signals} \mid \text{events})$ describes generative **forward model** based on knowledge of **seismology and seismometry**



Given new signals, compute **posterior probability**

$$P(\text{events} \mid \text{signals}) \propto P(\text{signals} \mid \text{events}) P(\text{events})$$

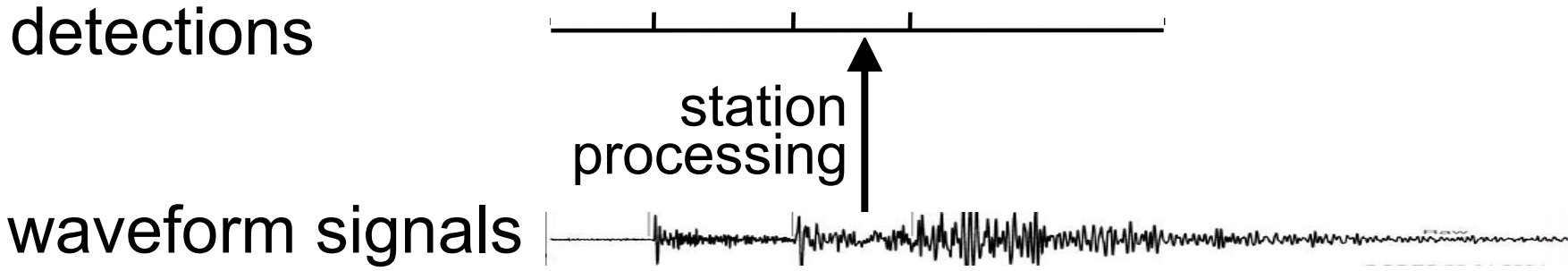
Advantages:

- Explicit model directly **encodes scientific understanding**
- Better models => better results
- Correctly incorporates **all evidence**, weighted by uncertainty

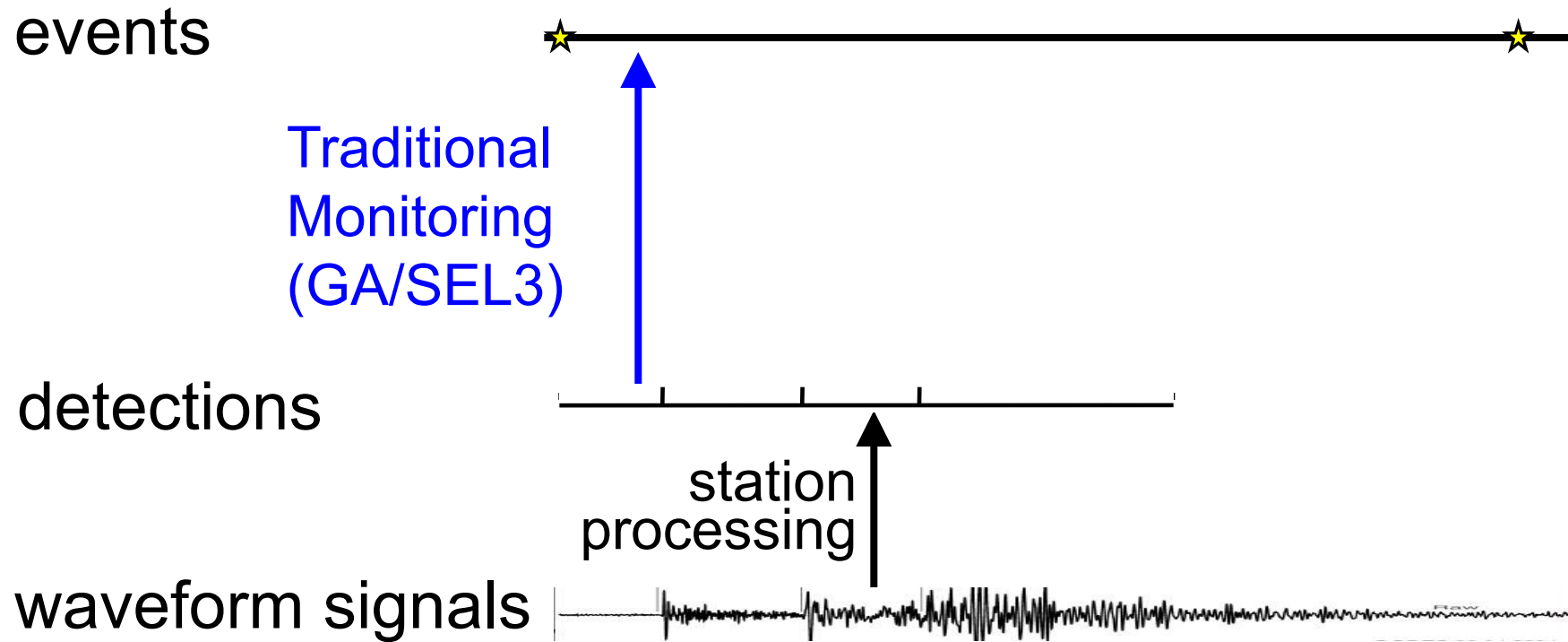
The space of monitoring systems

waveform signals 

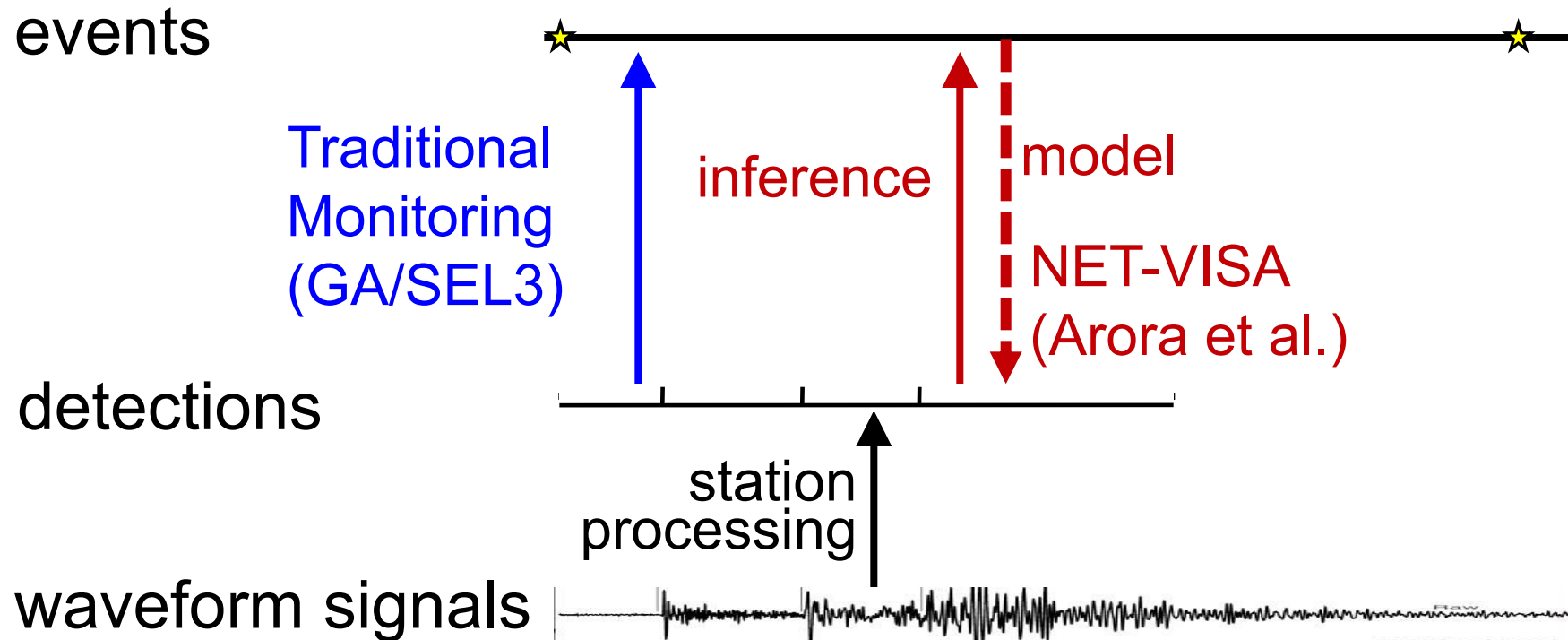
The space of monitoring systems



The space of monitoring systems

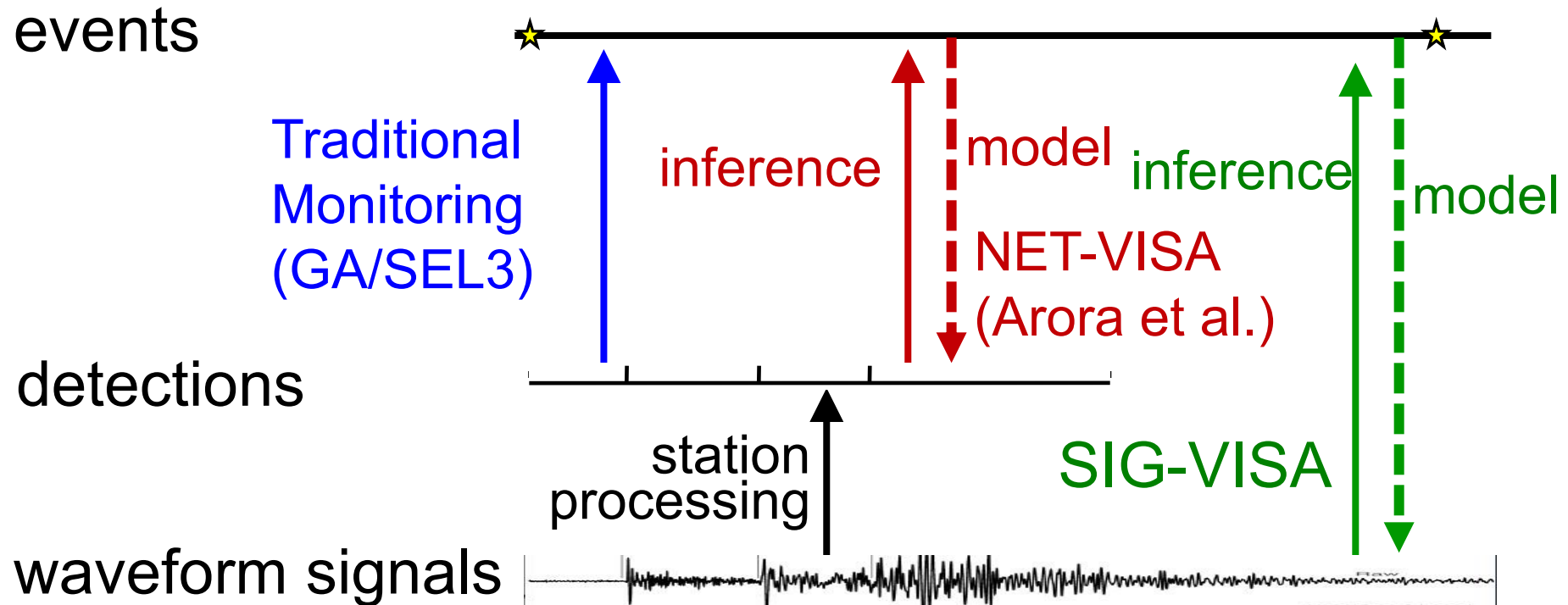


The space of monitoring systems



NET-VISA = detection-based

The space of monitoring systems



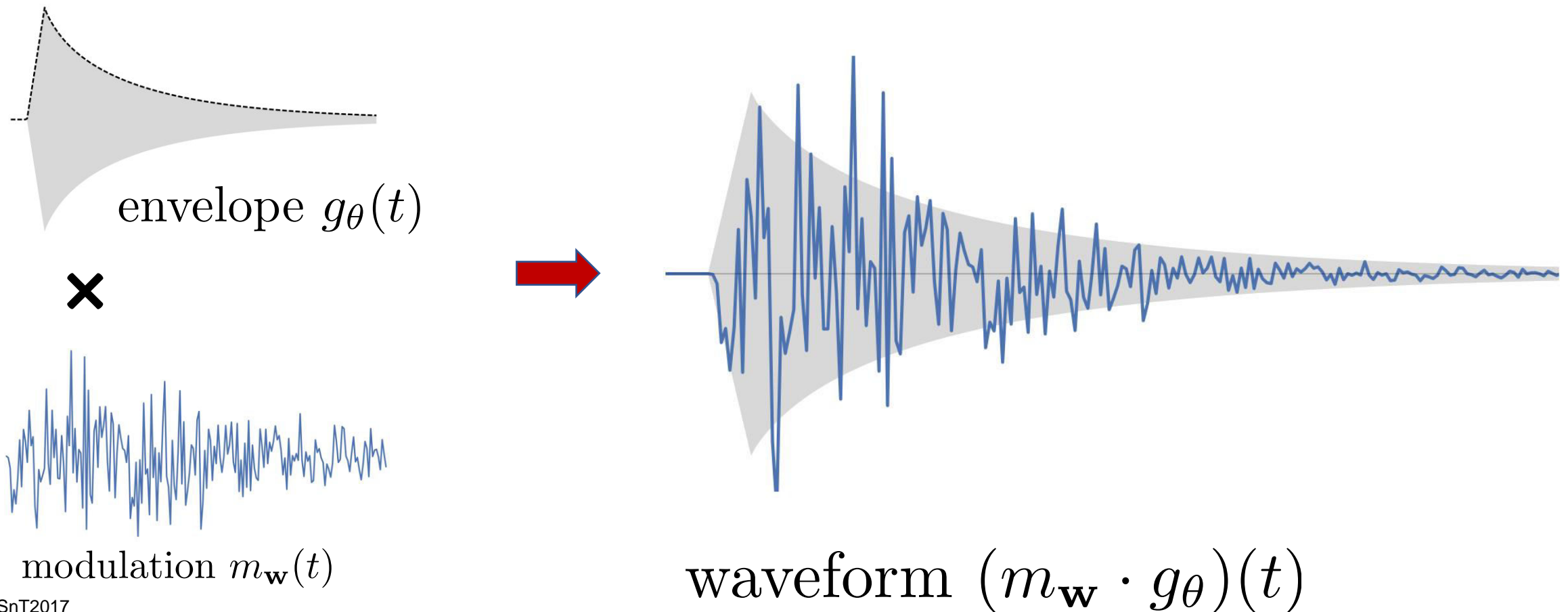
NET-VISA = detection-based, SIG-VISA = signal-based

What physics can we include?

- Travel time and attenuation models
 - > event location by triangulation
- Spatial continuity of travel-time residuals
 - > double differencing
- Spatial continuity of waveforms
 - > waveform matching
 - > sub-threshold detections

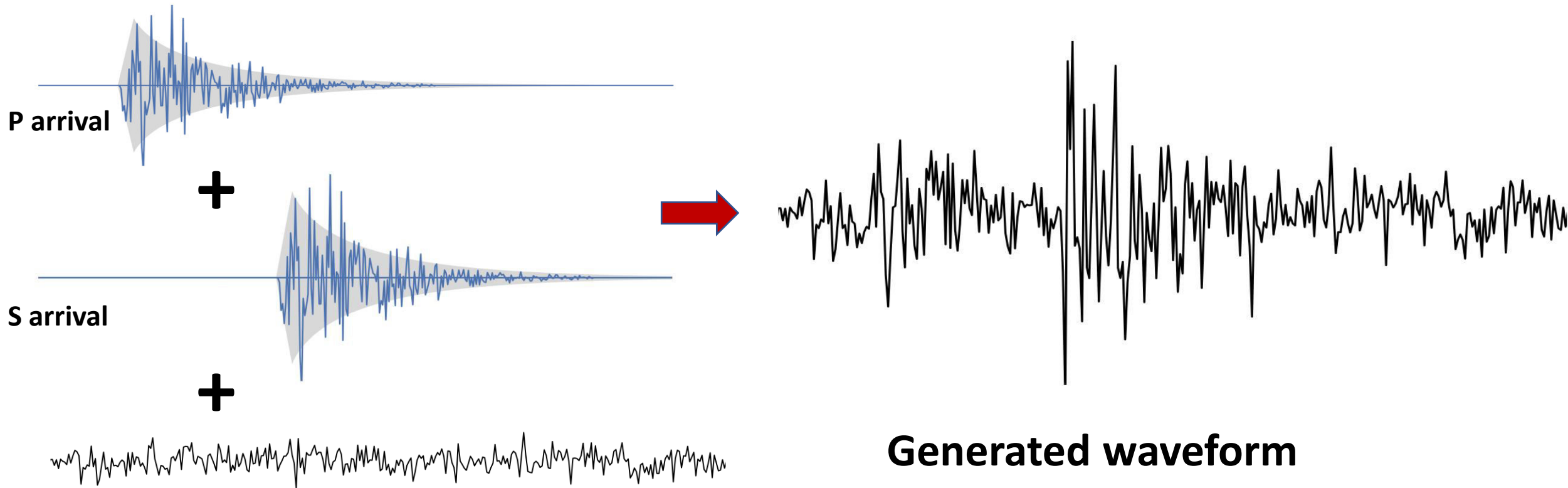
The SIGVISA forward model

Each arriving phase: parameterized *envelope* multiplied by stochastic *modulation process*.



The SIGVISA forward model

At each station: sum all phases of arriving events, plus autoregressive background noise.

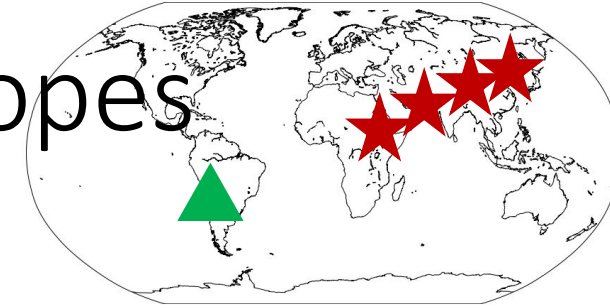


Generated waveform

$$s(t) = \epsilon(t) + \sum_{i=1}^{|\mathbf{e}|} (g_{\theta_i} \cdot m_{\mathbf{w}_i})(t)$$

Autoregressive noise process $\epsilon(t)$
(learned, station-specific)

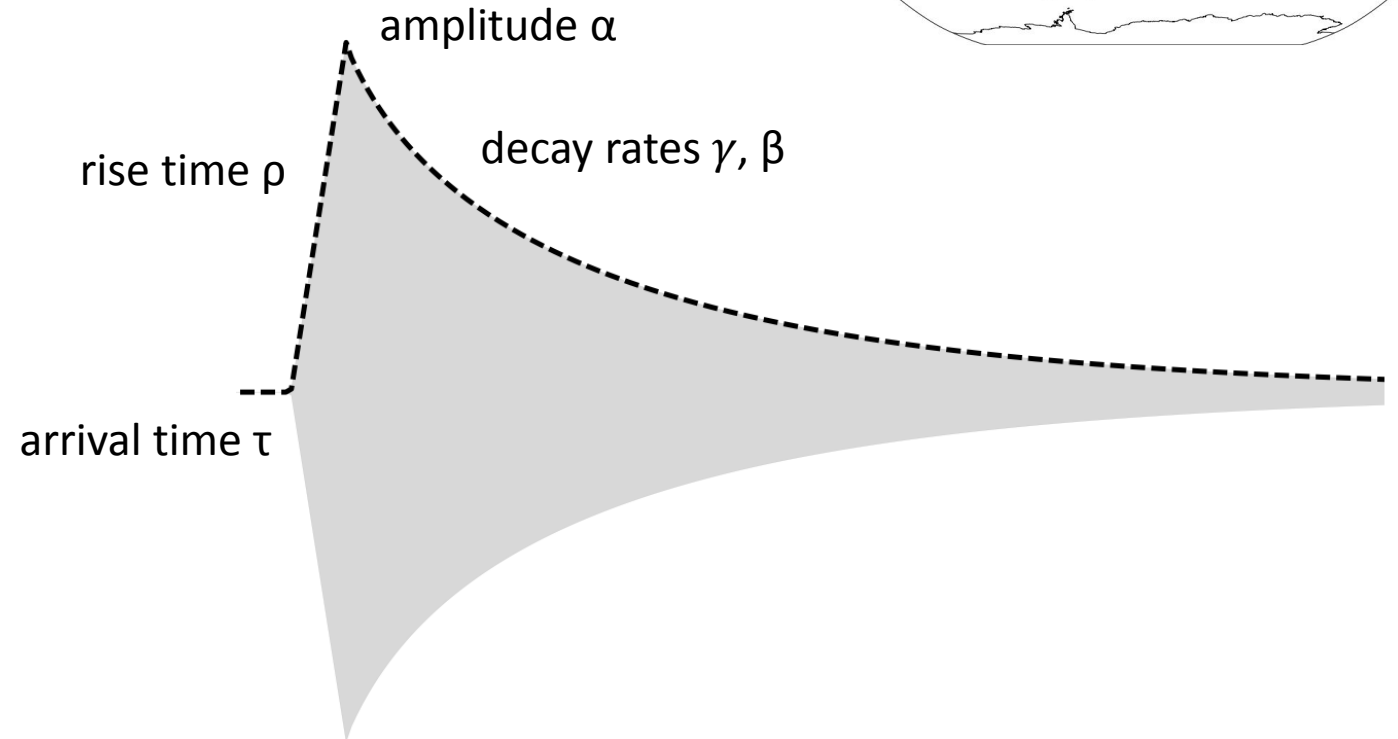
SIGVISA model: physics-driven envelopes



Waveform **envelope shape**

captures the essential physics used by detection-based monitoring.

We predict envelope parameters using **geophysical models** (IASPEI91 travel time model, Brune & Mueller-Murphy source amplitude models) given event distance, depth, magnitude.



Parametric envelope: linear rise, poly-exponential decay

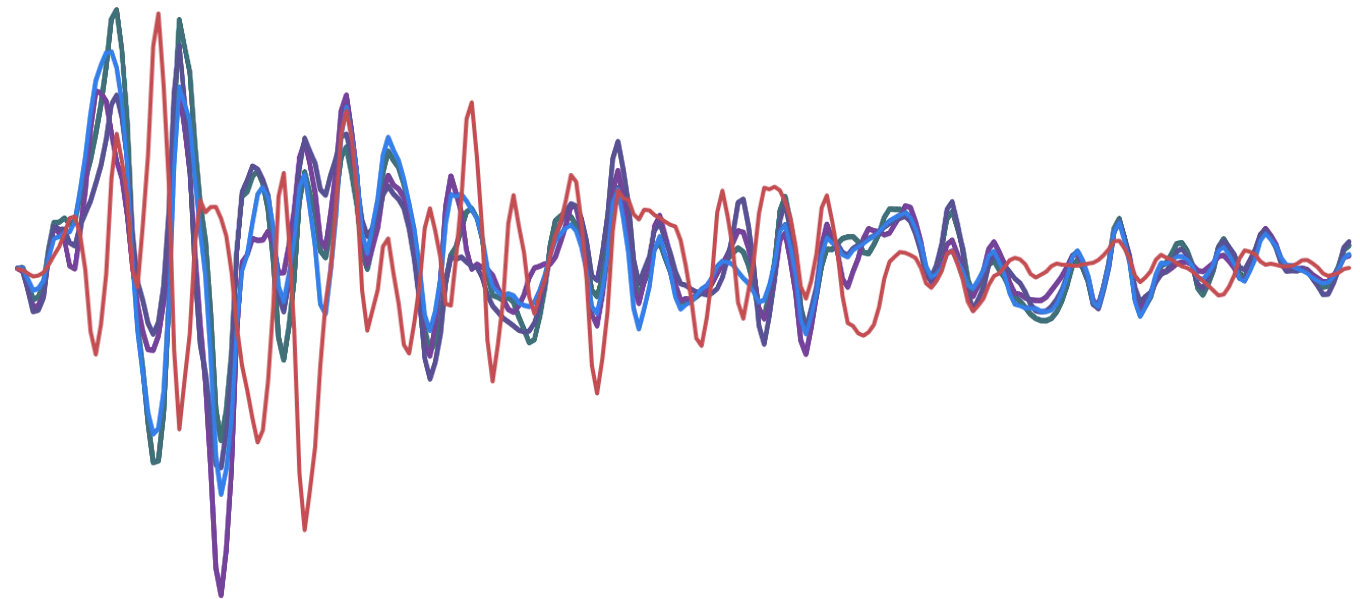
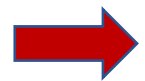
(Mayeda et al., 2003; Cua 2005)

SIGVISA model: spatial continuity of waveforms

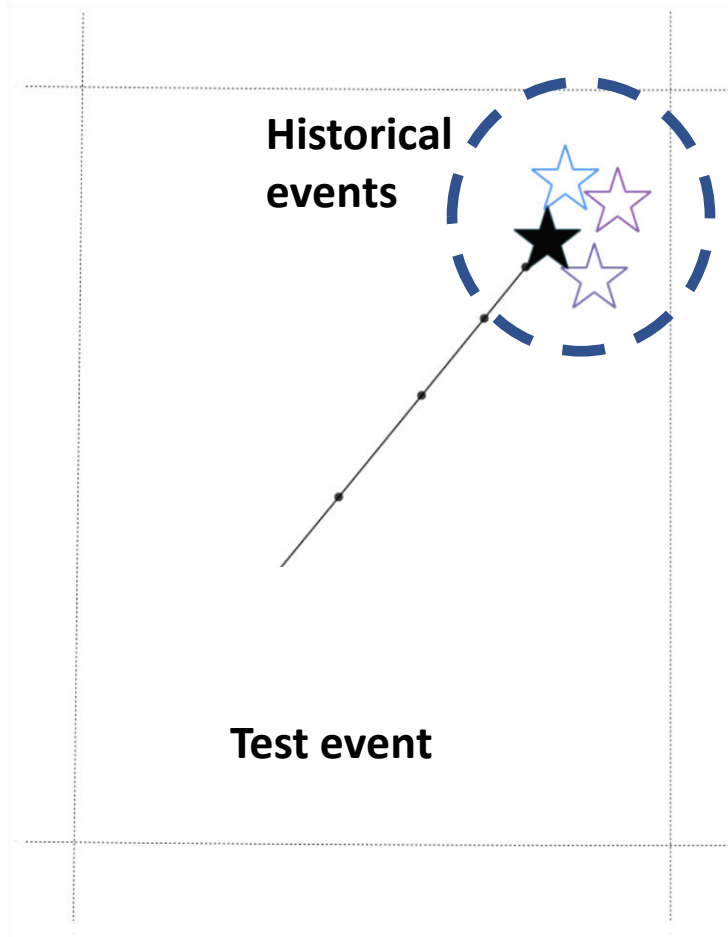
To enforce repeatability and spatial continuity: model modulation wavelets \mathbf{w} using Gaussian processes (i.e., kriging) conditioned on source event location.

-> Nearby events generate correlated signals.

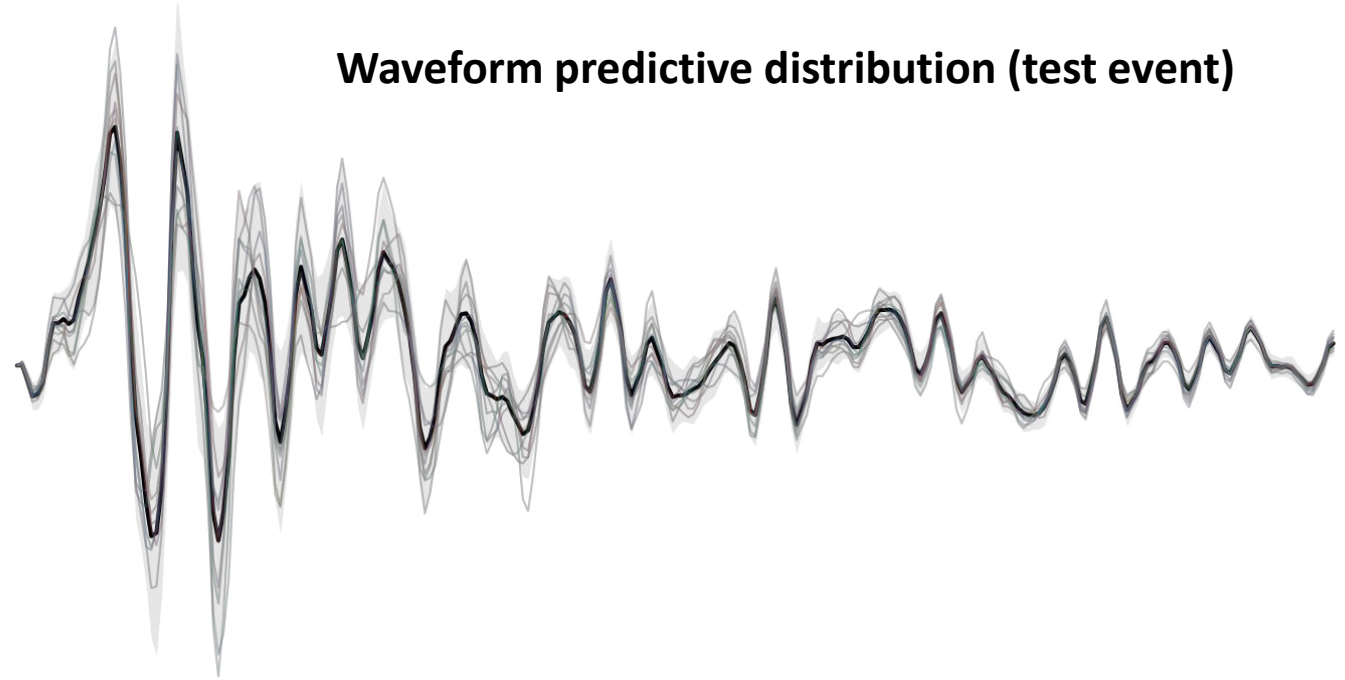
$$p(\mathbf{w}|\mathbf{e}) = \text{GP}(0, k(\mathbf{e}, \mathbf{e}))$$



Forward model conditioned on historical data



Waveform predictive distribution (test event)

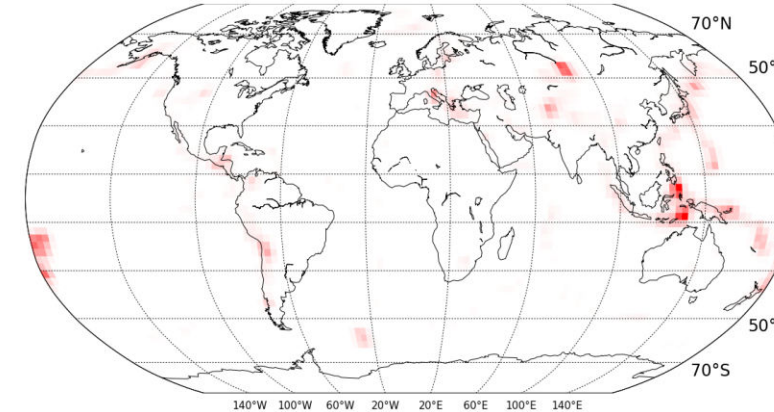


Far from training events: model predicts rough envelope shape, uncertain about specific waveform

Near historical events: model predicts waveform observed from previous events

Bayesian inference: inverting the forward model

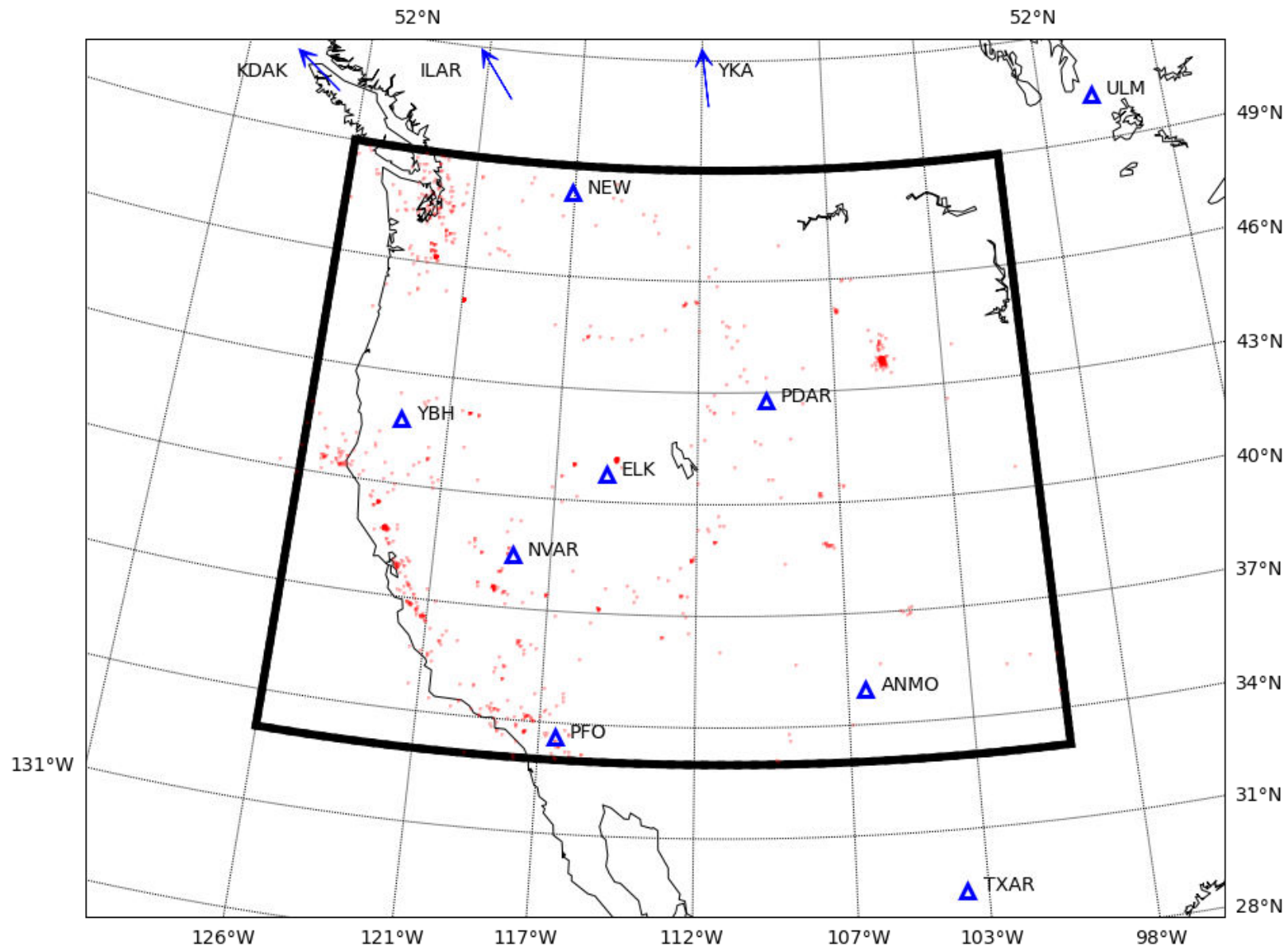
- Inference searches over latent explanations (event bulletins), scored by posterior probability
$$P(\text{events} \mid \text{signals}) \propto P(\text{signals} \mid \text{events}) P(\text{events})$$
- We use reversible jump Markov Chain Monte Carlo (RJMCMC) to draw posterior samples.
 - Efficient mixing requires careful proposal design for event birth and death moves, envelope parameters, etc.
 - We run multiple chains and merge results to avoid local optima.
- Sampler implicitly sums over all possible "picks" of each event (no hard detections).
- Feasible: using 80 machines, processes two weeks of signal data in 48hrs.



Results: monitoring the Western US

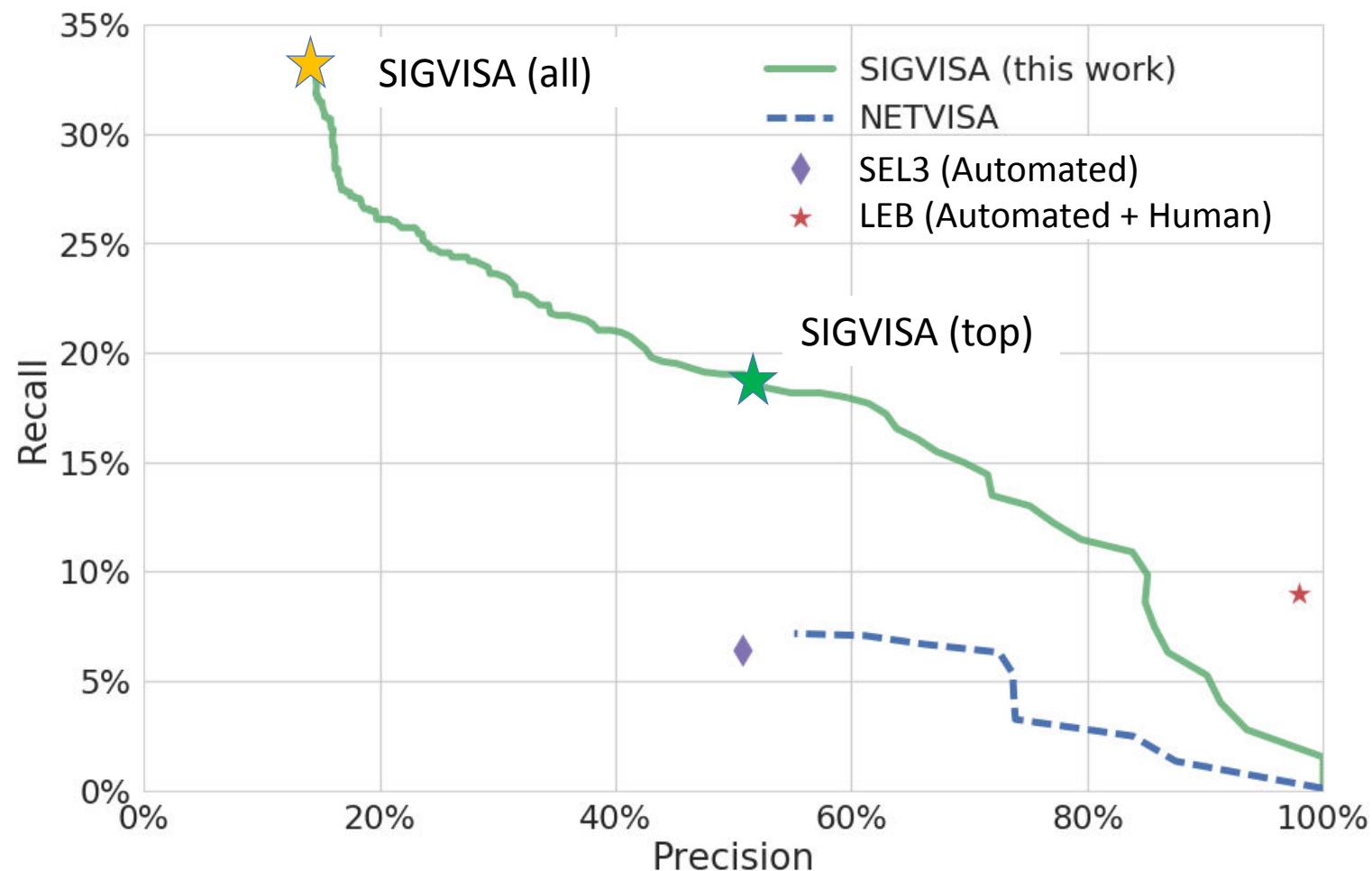
- Two-week period following Feb 2008 event at **Wells, NV** (6.0).
- Reference bulletin: **ISC regional catalog**, with Wells aftershocks from transportable US Array.
- Comparison of IMS-based systems:
 - SIGVISA (this work, signal-based Bayesian)
 - NETVISA (detection-based Bayesian)
 - SEL3 (existing automated bulletin)
 - LEB (reviewed by human analysts)
- SIGVISA given only array *reference stations* (no azimuth/slowness)!

Historical catalog (one year, 1025 events)

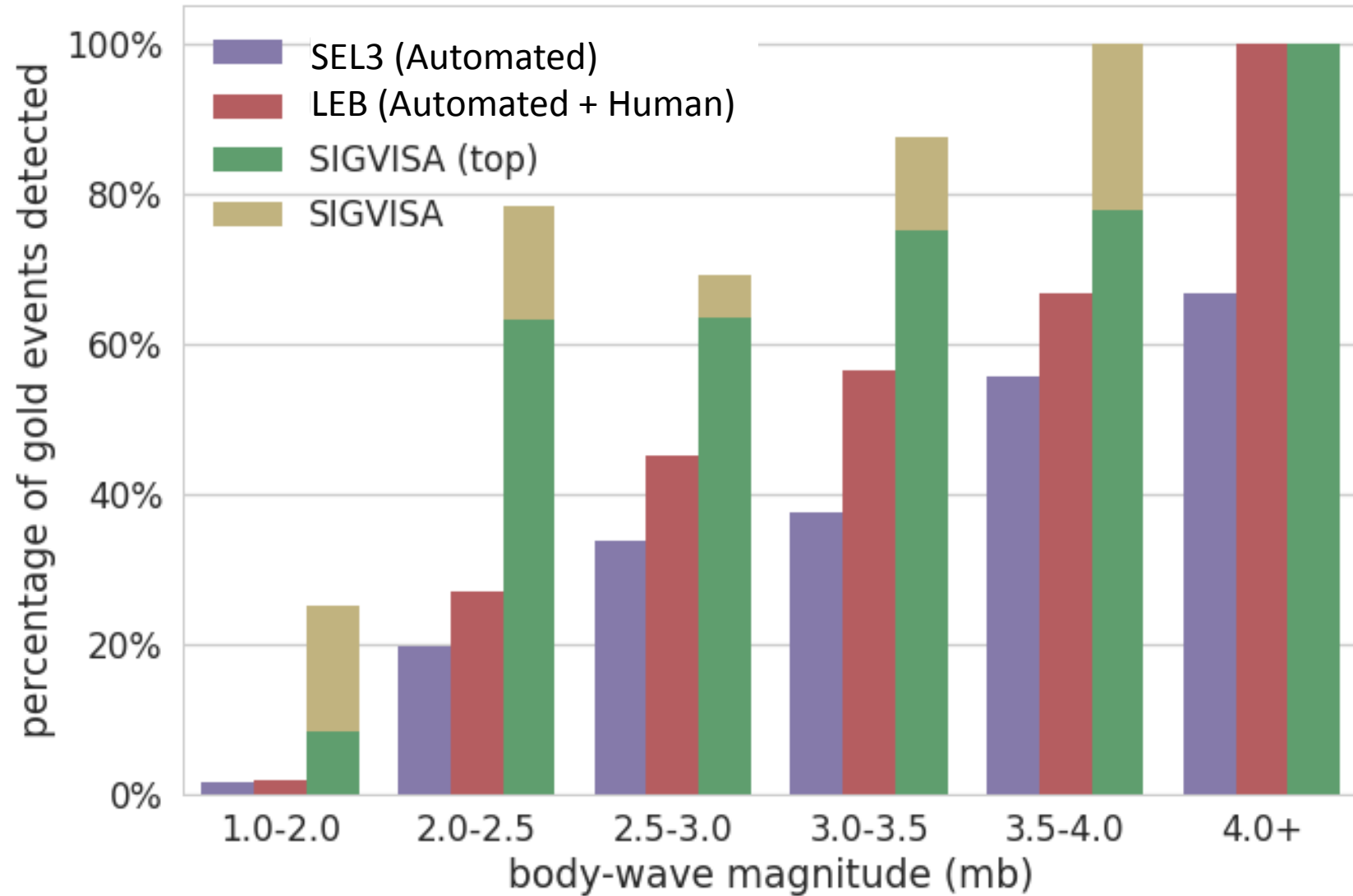


Evaluation: precision/recall

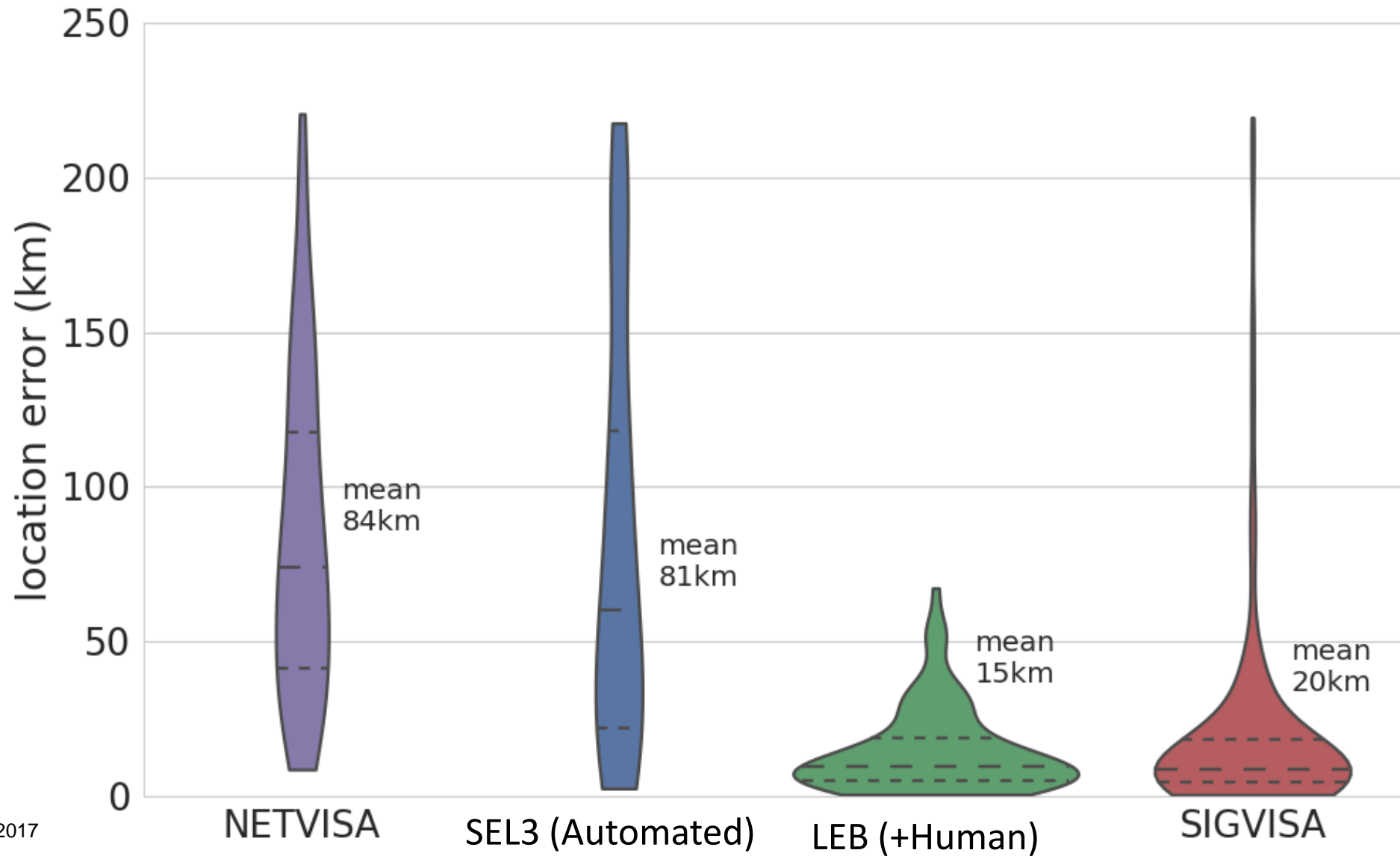
- Match inferred events to reference bulletin ($\leq 50s$, $\leq 2^\circ$ hard cutoff)
- **Precision:** of inferred events, % in reference bulletin.
- **Recall:** of reference events, % that were inferred.



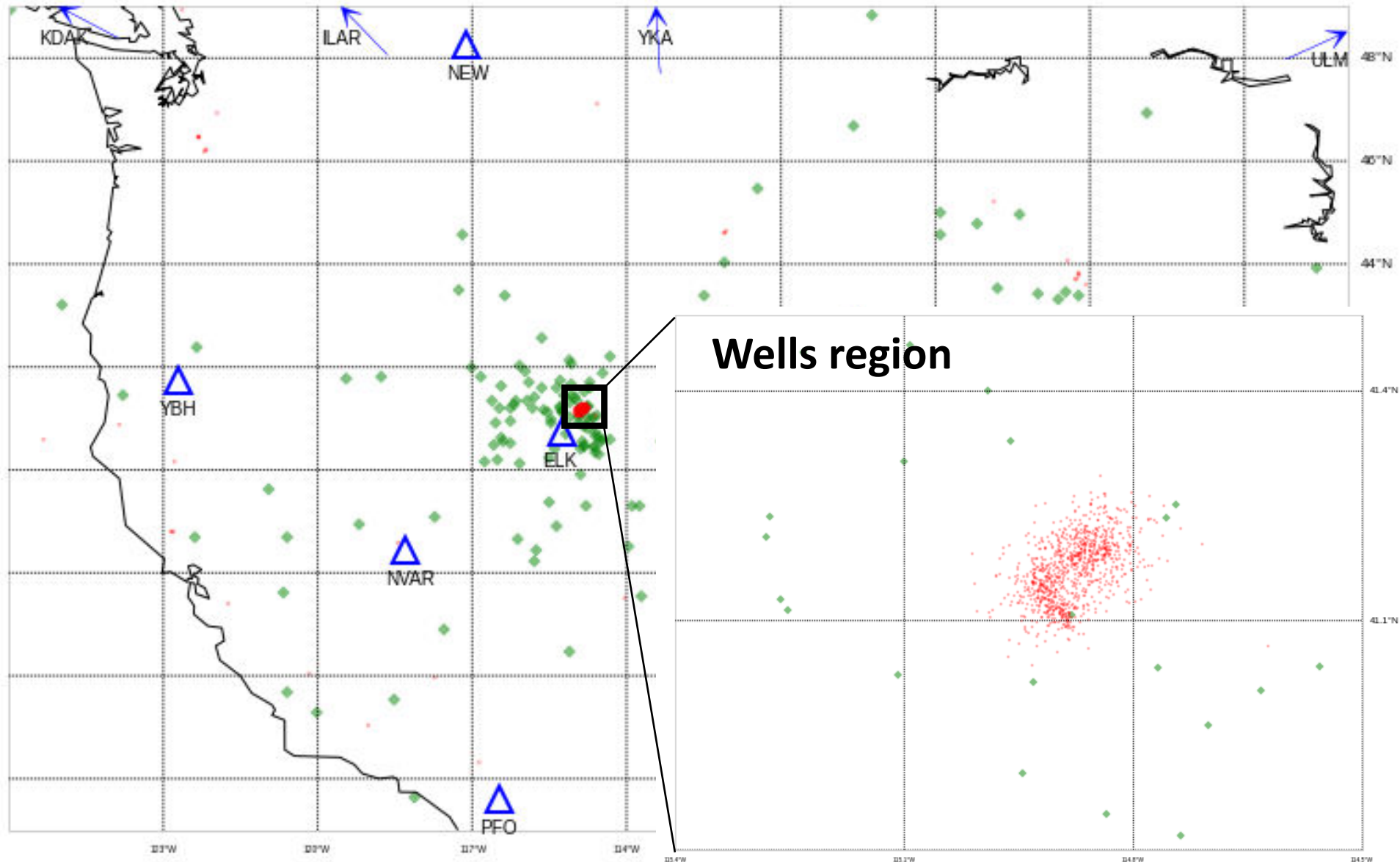
Recall by magnitude range



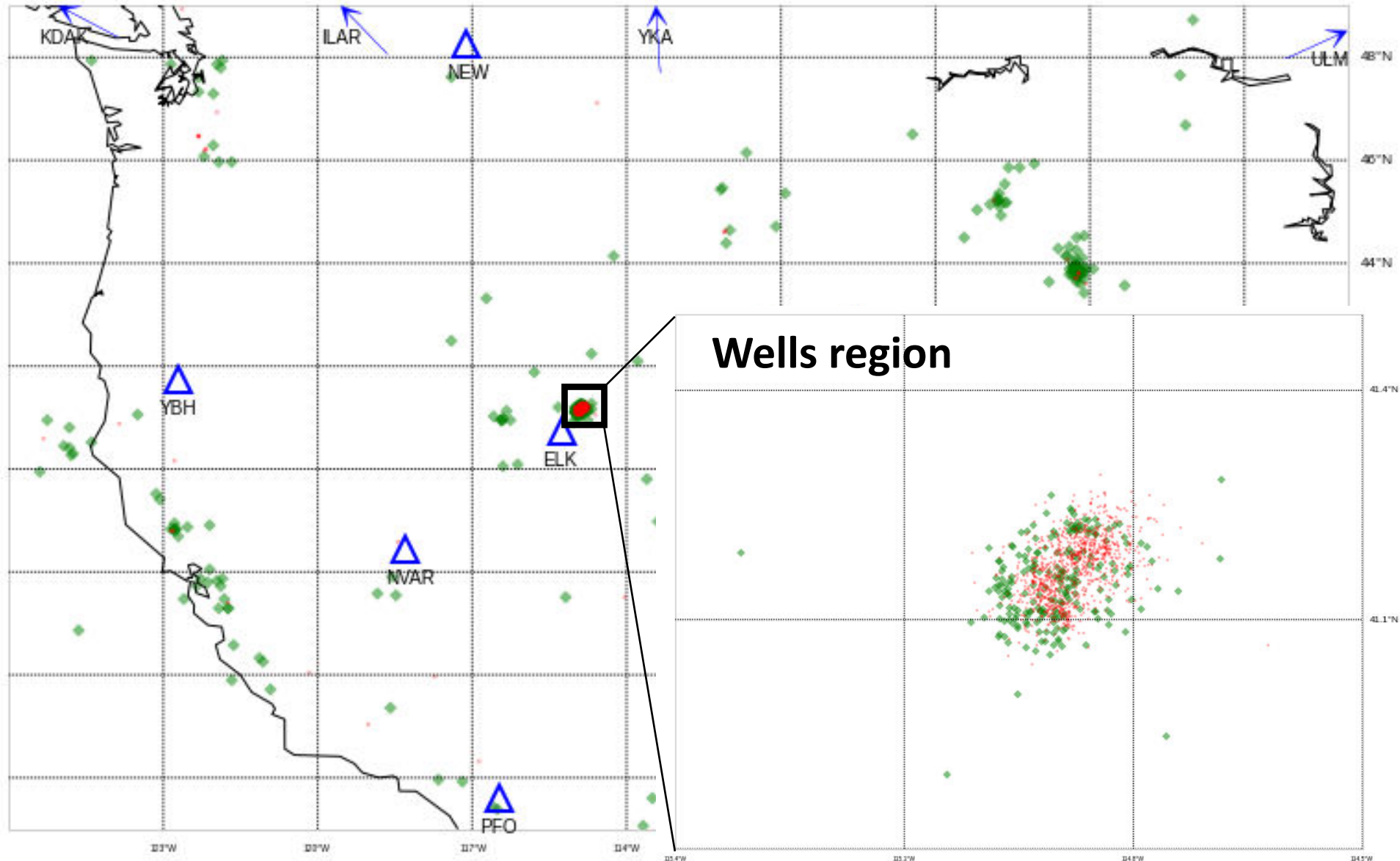
Distribution of location errors (km)



NETVISA (139 events)

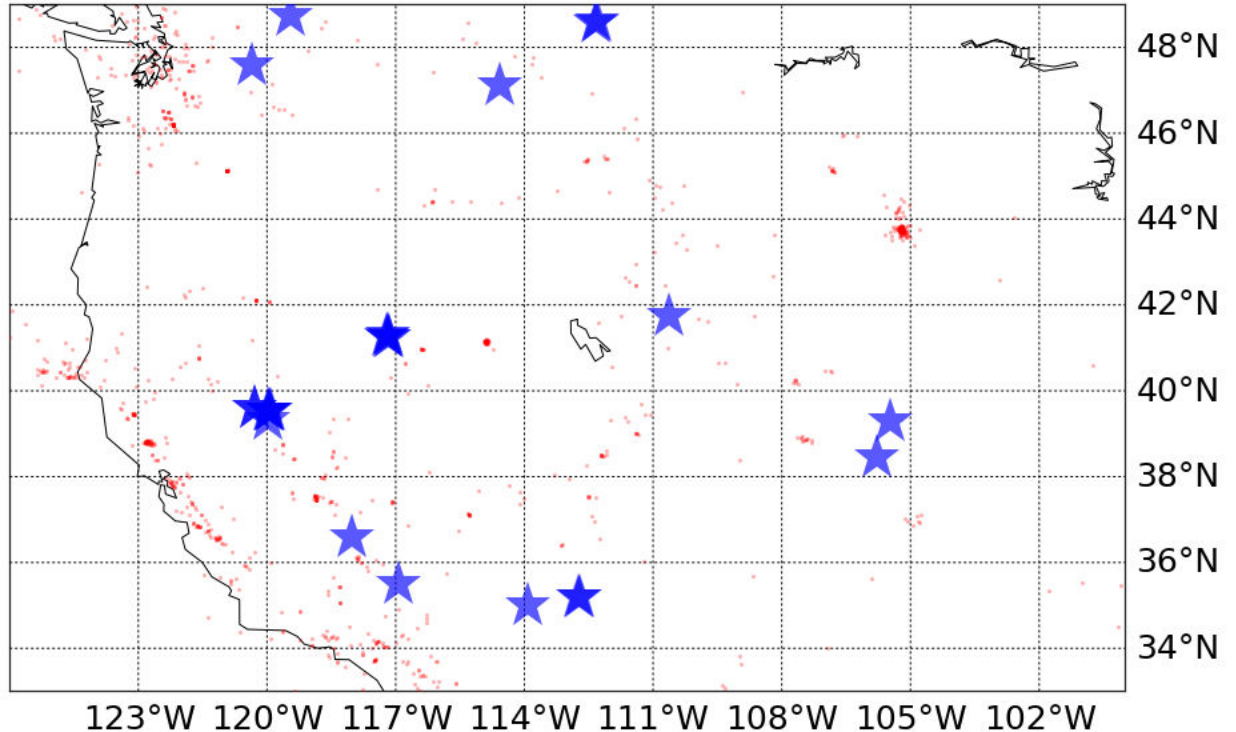


SIGVISA top events (393)

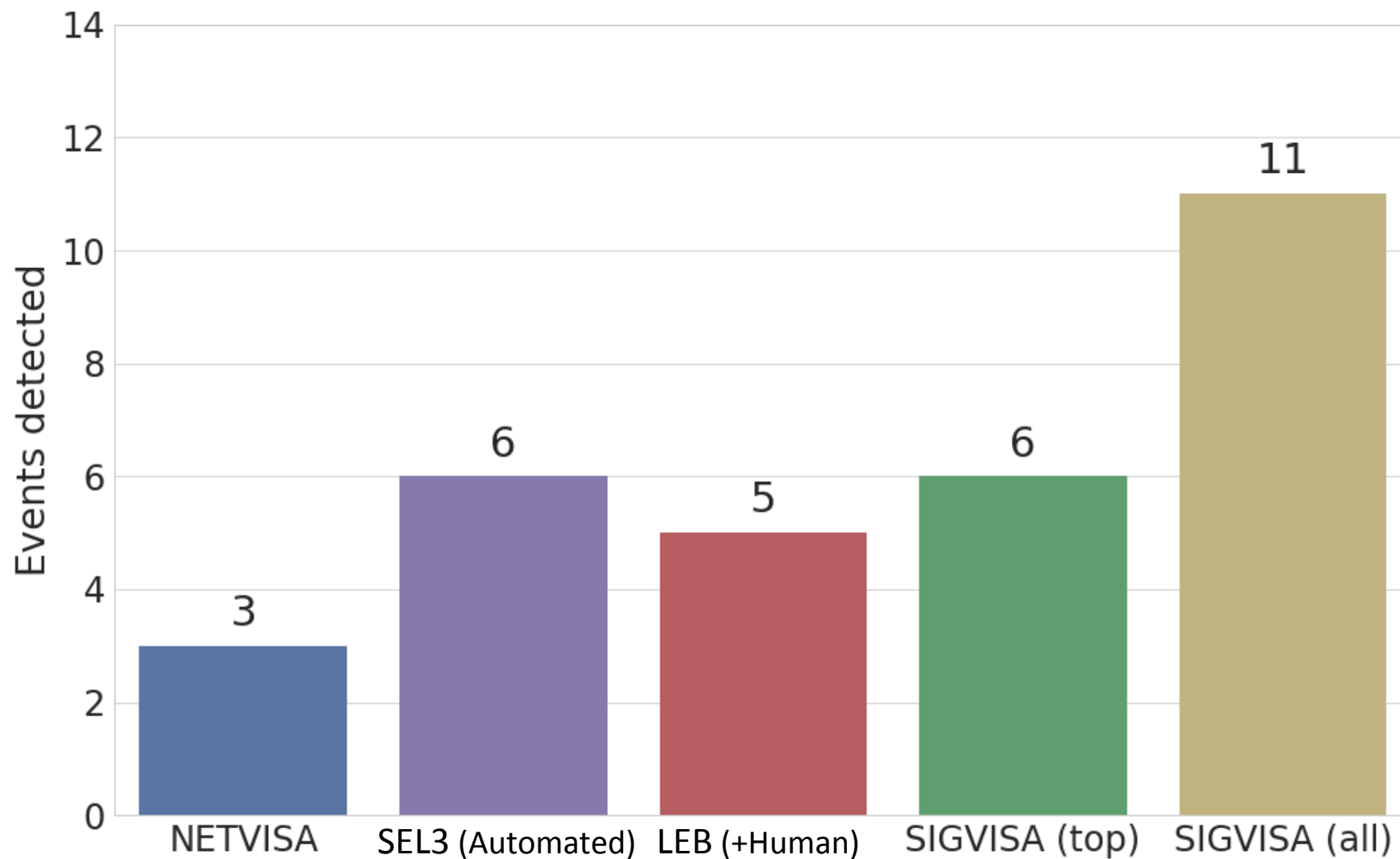


De novo events

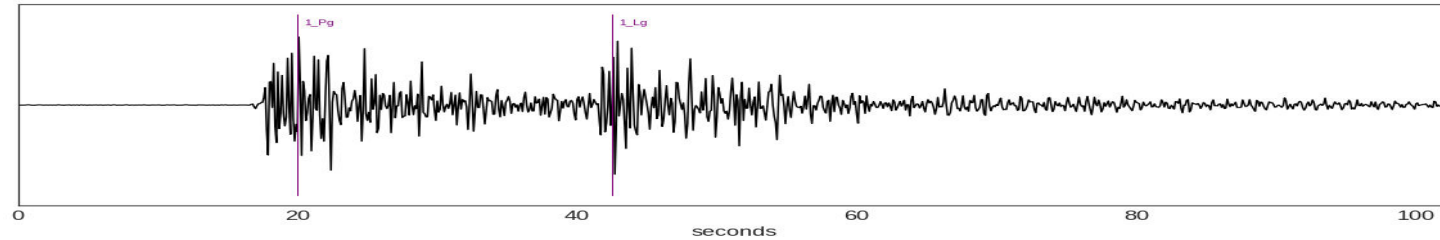
- Nuclear monitoring may involve events in areas with no known prior seismicity.
- Define *de novo* events as $\geq 50\text{km}$ from recorded historical event.
- ISC bulletin contains **24 such events** between January and March 2008.



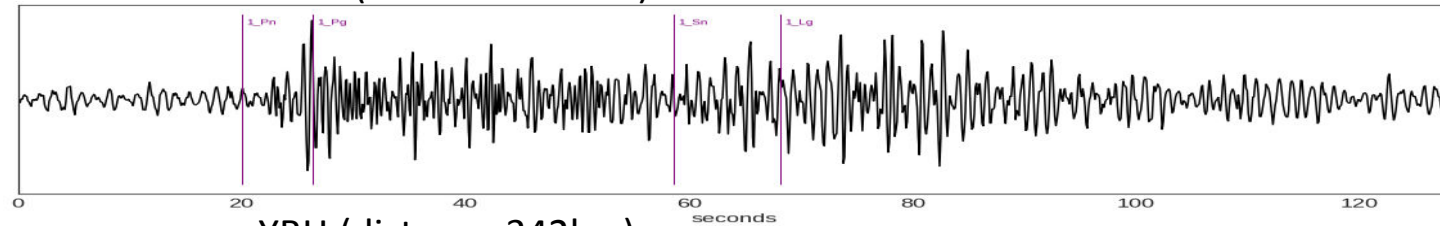
Recall of *de novo* events (# detected / 24)



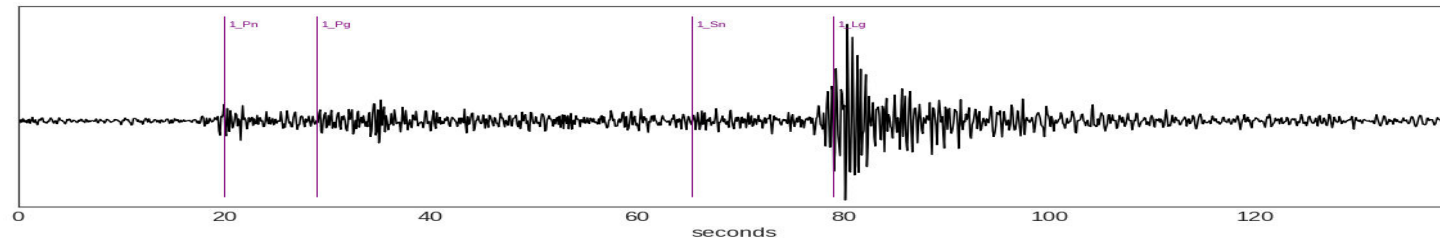
An event missed by LEB/SEL3/NETVISA



NVAR (distance 183km)



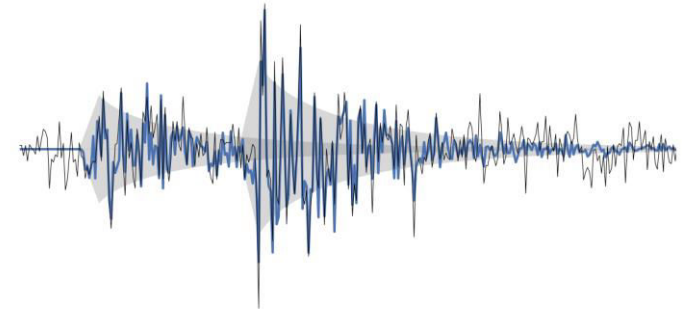
YBH (distance 342km)



ELK (distance 407km) **NO DETECTIONS REGISTERED**

- ISC evid 13484219, located by SIGVISA at 119.79°W, 39.60°N.
- Seemingly due to picking error: no detections registered at ELK despite clear signal.

Conclusions



- SIGVISA infers seismic events directly from observed waveforms using model-based Bayesian inference.
- Our model **encodes physical assumptions** of both detection-based and waveform matching approaches.
 - Inverting these assumptions recovers advantages of waveform matching where historical data are present, otherwise degrades smoothly to envelope matching.
- Inference achieves recall **3X existing systems** at same precision, while also recovering *de novo* events missed by human analysts.