Non-ergodic Ground Motion Models and Near-Fault Data Contributions

SCEC Near-fault Observatory

Grigorios Lavrentiadis[1,2] Elnaz Seylabi[3] Nicholas M. Kuehn[2] Xiaofeng Meng[4] Yousef Bozorgnia[2] Christine A. Goulet[4] Albert R. Kottke[5]

[1]California Institute of Technology [2]University of California, Los Angeles

[3]University of Nevada Reno [4]University of Southern California

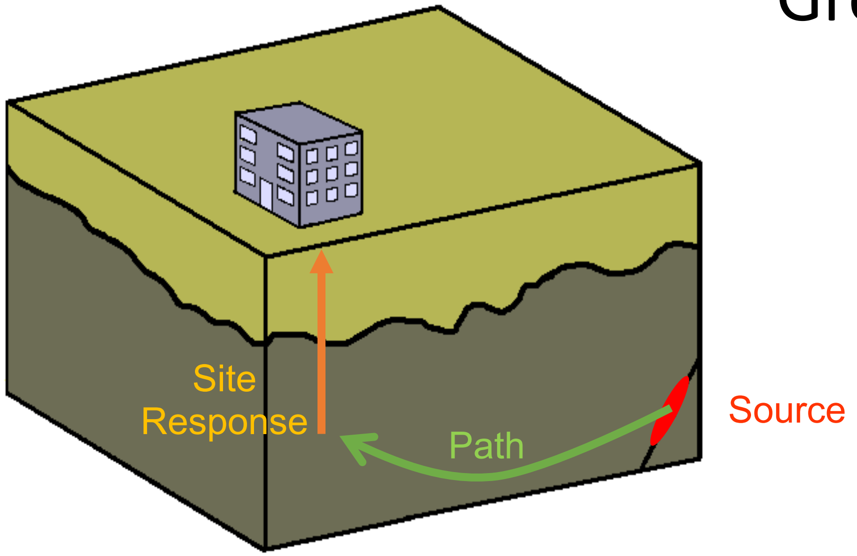
[5]Pacific Gas & Electric Company

October 27, 2022

Why the shift to non-ergodic GMMs?

- Quantify the "true" level of hazard uncertainties
- Demonstrates the value of local data
- Potential of reducing ground-motion design values
  (especially at large return periods)

Ground Motion Models (GMMs)



Adapted from X. Meng and J. Stewart

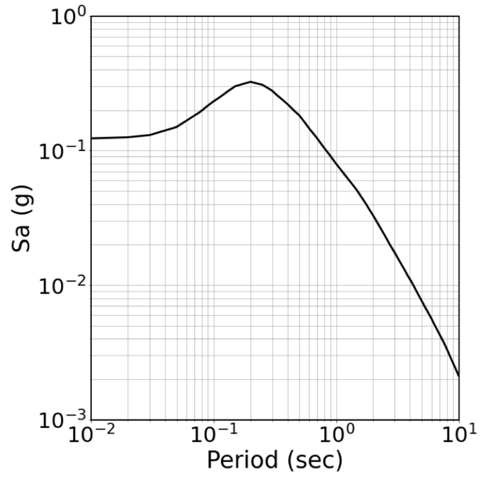
Ground Motion = Source × Path × Site

$$f_{GMM} = f_M(M, SOF, \dots) + f_P(R_{rup}, \dots) + f_S(V_{S30}, \dots)$$

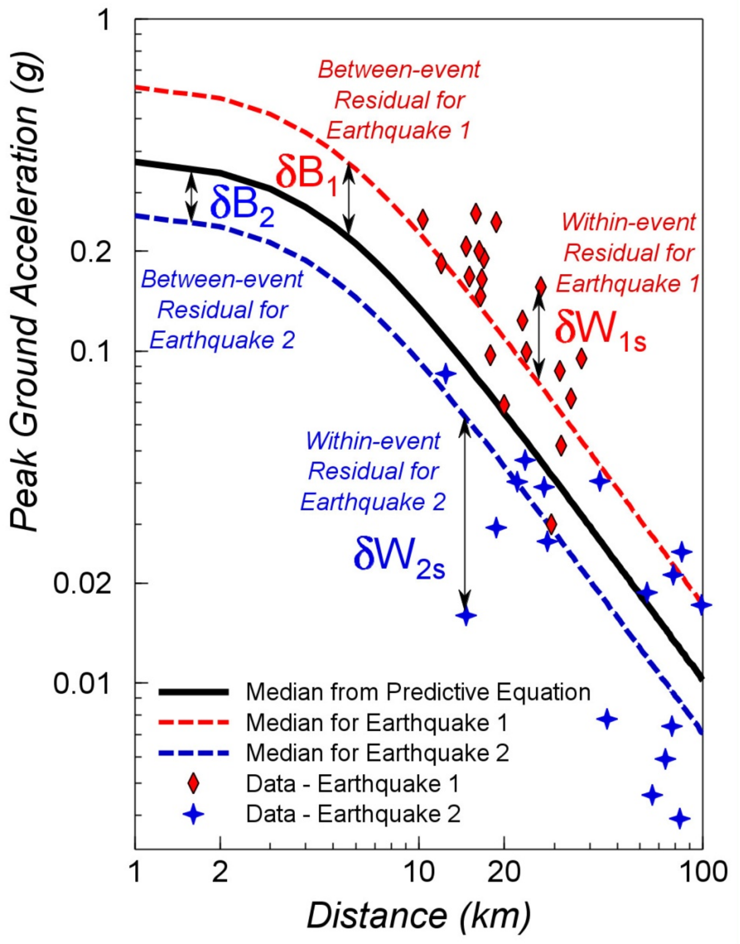
Energy Release

Anelastic Attenuation, Scattering, …

Site Amplification, Basin Effects, …



Can everything be explained? (Aleatory Variability)



Reproduced from Al Atik et al. 2010 and Strasser et al 2009

Aleatory Terms

$$\ln(PSa) = f_{GMM}(M, R_{rup}, \ldots) + \delta B_e + \delta Wes$$

Between Event Term

Within Event Term

Sources of Aleatory Variability:

- True Randomness

  e.g. stress distribution

- Model Simplifications

  e.g. site amplification described V_{S30}

This is where Ergodic and Nonergodic GMM are different!

Non-ergodic Effects

- $\delta L2L$: Systematic difference in GM due to source effects compared to a reference GMM
  (e.g., due to systematic differences in median regional stress-drop)
- $\delta P2P$: Systematic difference in GM between a site-source pair and a reference GMM
  (e.g., due to differences in anelastic attenuation)
- $\delta S2S$: Systematic deviation of GM at a site from reference a GMM
  (e.g. due to differences in velocity profiles for a given V_{S30})

Epistemic Terms: $\delta L2L_e$, $\delta P2P_{es}$, $\delta S2S_s$ — Aleatory terms: δW_{es}^0, δB_e^0

Residuals: $\delta W_{es} + \delta B_e \approx \delta L2L_e + \delta P2P_{es} + \delta S2S_s + \delta W_{es}^0 + \delta B_e^0$

St. Dev.: $\phi^2 + \tau^2 \approx \tau_{L2L}^2 + \phi_{P2P}^2 + \phi_{S2S}^2 + \phi_0^2 + \tau_0^2$

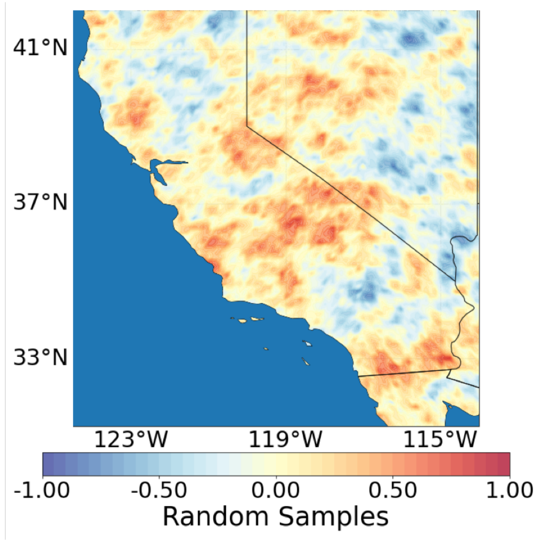
Ergodic Components | Non-ergodic Components

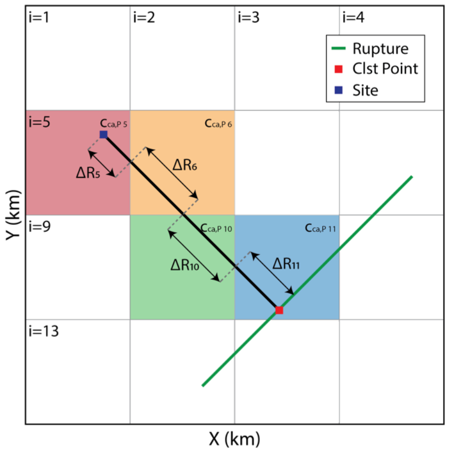
NGMM Formulation

Ergodic Base Model — Event Coordinates — Site Coordinates — Cell-specific Anelastic Attenuation

$$f_{nerg}(M, R_{rup}, \ldots, \vec{t}_E, \vec{t}_S) = f_{erg}(M, R_{rup}, \ldots) + \delta c_{1,E}(\vec{t}_E) + \delta c_{1,S}(\vec{t}_S) + \Delta \vec{R} \cdot \vec{c}_{ca,P}$$

- Spatially varying coefficients model the source and site effects
- Cell specific anelastic attenuation models the path effects

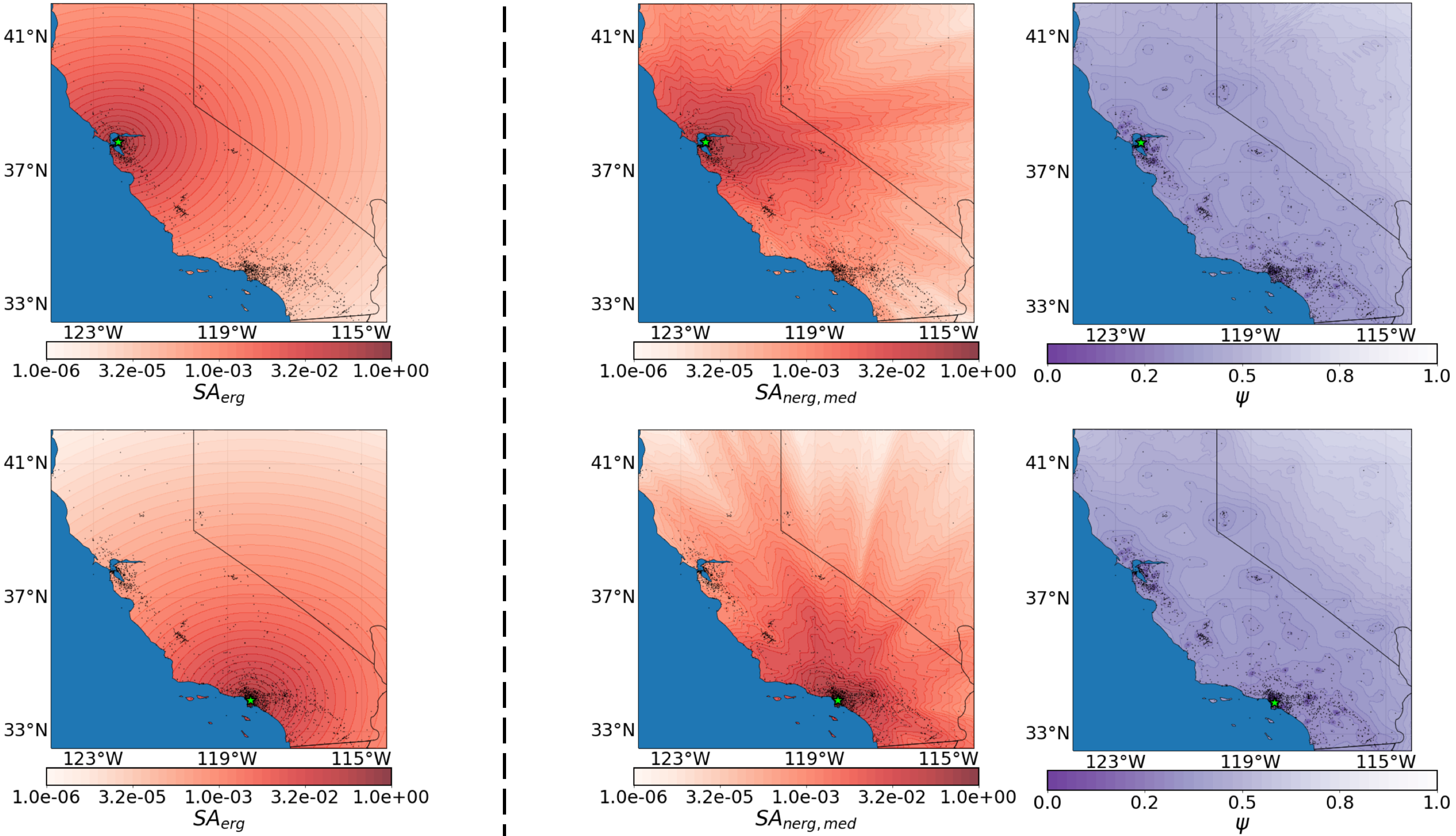




Ergodic vs Nonergodic GMMs

Earthquake
in Bay Area

Earthquake
in Los Angeles

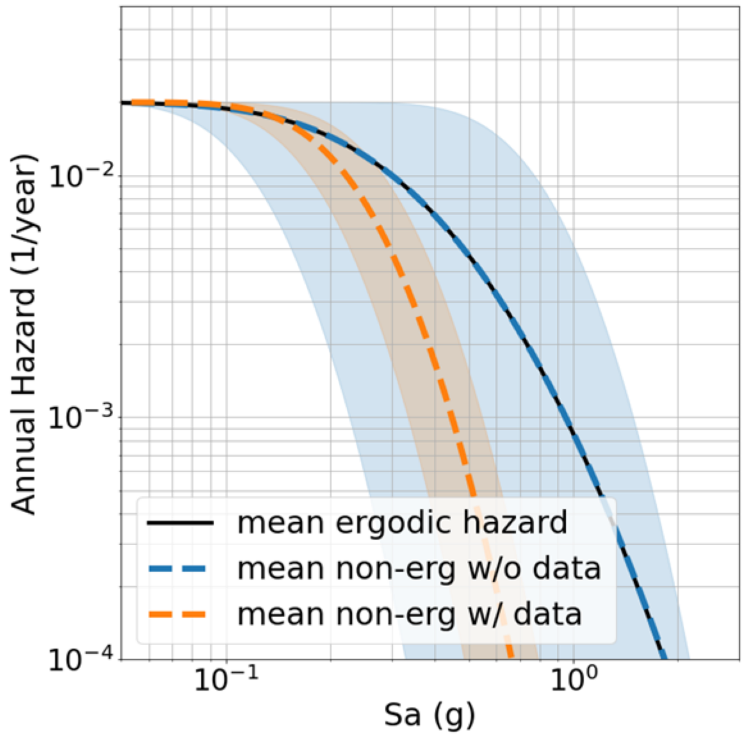


Ergodic GMM

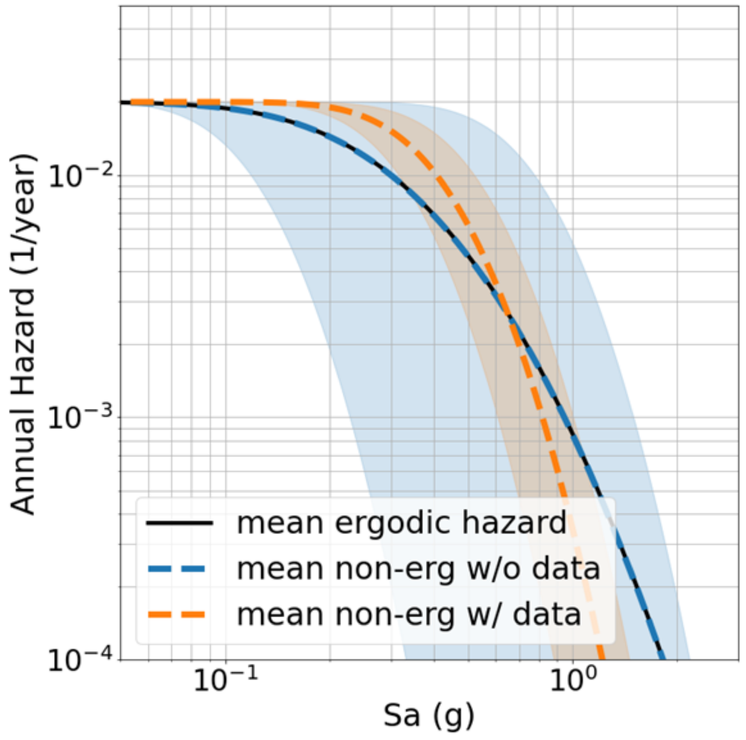
Non-ergodic GMM

Ergodic versus Nonergodic PSHA

Reduced σ leads to steeper hazard curves



Site1: Negative systematic effects



Site2: Positive systematic effects

Contributions of Near Fault Observatory

What are the key science contributions with small and moderate earthquakes?

- Separation of the different non-ergodic effects
- Better understanding of the phenomena controlling the non-ergodic source effects
- Modeling of radiation patterns and directivity effects (magnitude and distance dependence)

Contributions of Near Fault Observatory

What are the key science contributions with large earthquakes?

For ground-motion model development:

- Modeling of large magnitude saturation at short distances
- Predictability of large magnitude non-ergodic source effects using small earthquakes

For surface fault rupture model development:

- Correlation between ground motion and permanent tectonic displacement

Contributions of Near Fault Observatory

How will efforts in this topical area contribute to / encourage/ enable training the next generation of technologists and researchers?

- Provides a unique set of data for the validation of numerical simulations and empirical GMMs for near-fault effects

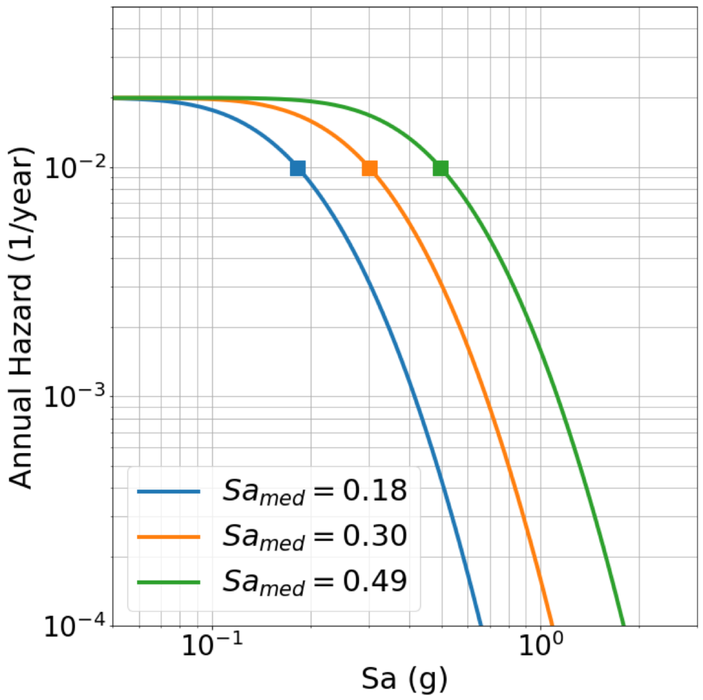
Contributions of Near Fault Observatory

Justification for the geometry, scale, spacing etc. for the choices made- or identify if modeling is still needed?

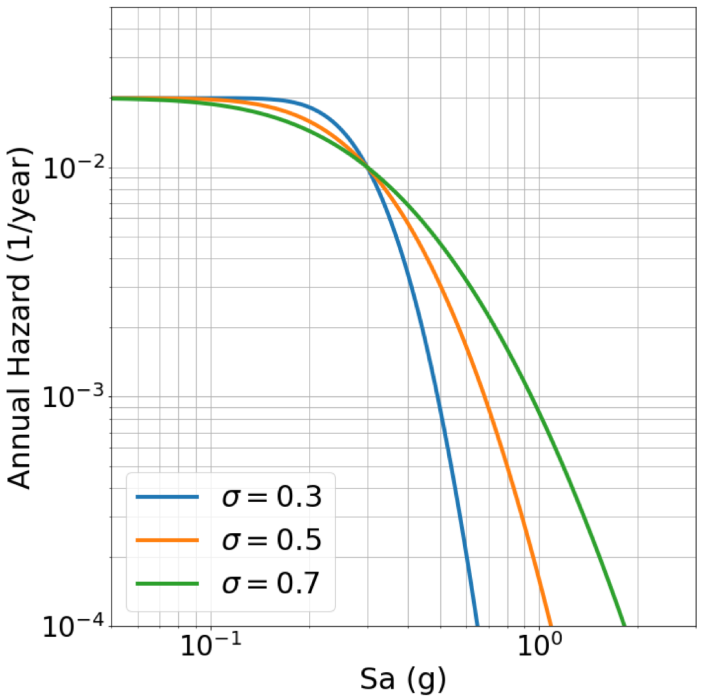
- Based on available strong-motion datasets, length-scales of the non-ergodic source and site effects are in the order of 30 and 10km respectively
- Shorter instrument spacing could discover finer spatial variations.

Supplemental Slides

Effects of GMM on PSHA



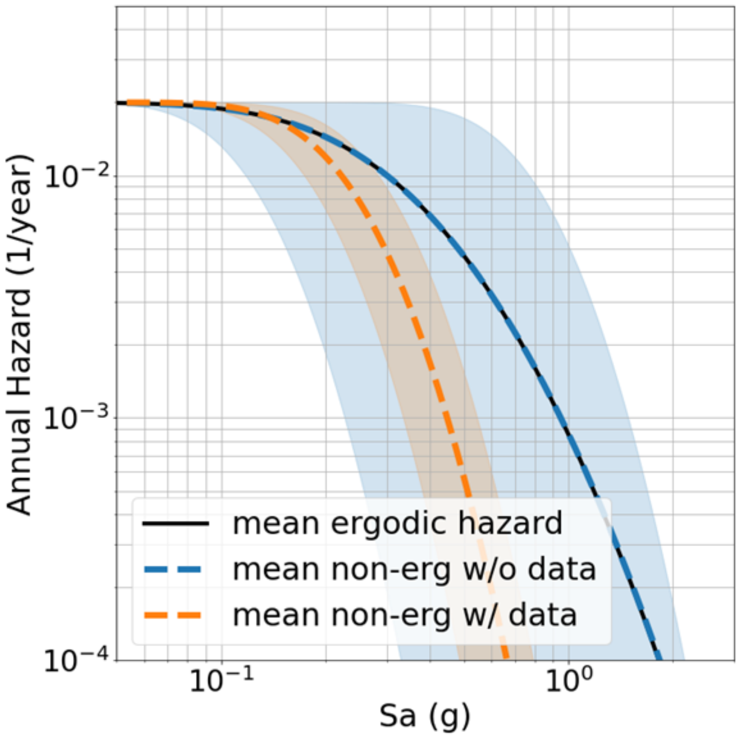
Effect of GMM median



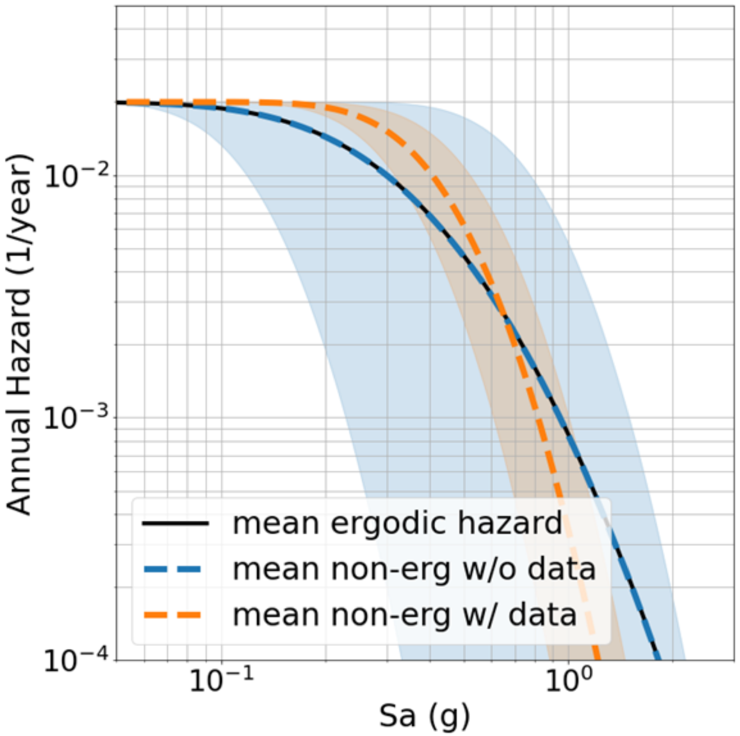
Effect of GMM standard deviation

Ergodic versus Nonergodic PSHA

Reduced σ leads to steeper hazard curves



Site1: Below average systematic effects



Site2: Above average systematic effects

NGMM Formulation

$$f_{nerg}(M, R_{rup}, \dots, \vec{t}_E, \vec{t}_S) =$$

$$f_{erg}(M, R_{rup}, \dots) + \delta c_{1,E}(\vec{t}_E) + \delta c_{1,S}(\vec{t}_S) + (path)$$

Ergodic Base Model

Event Coordinates

Site Coordinates

- Spatially varying coefficients are commonly used to model source and site effects

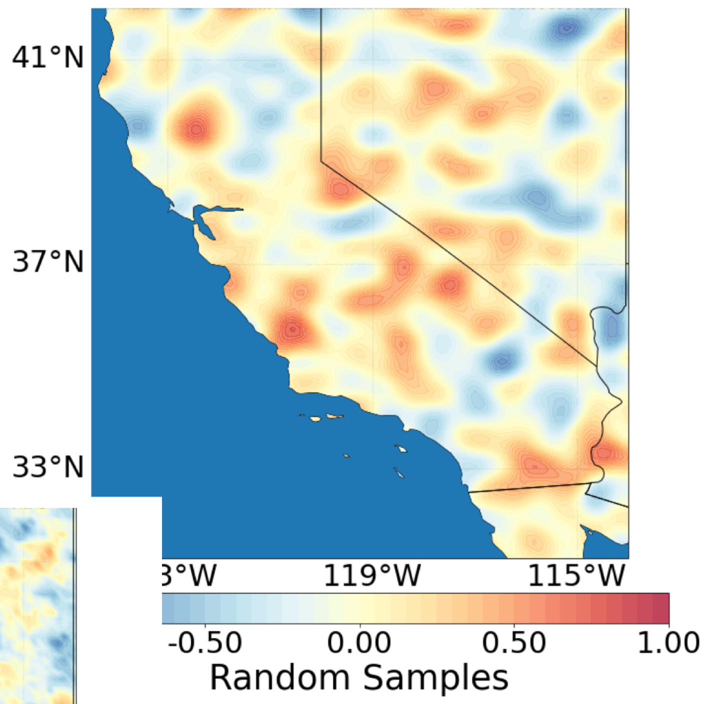
Gaussian Process

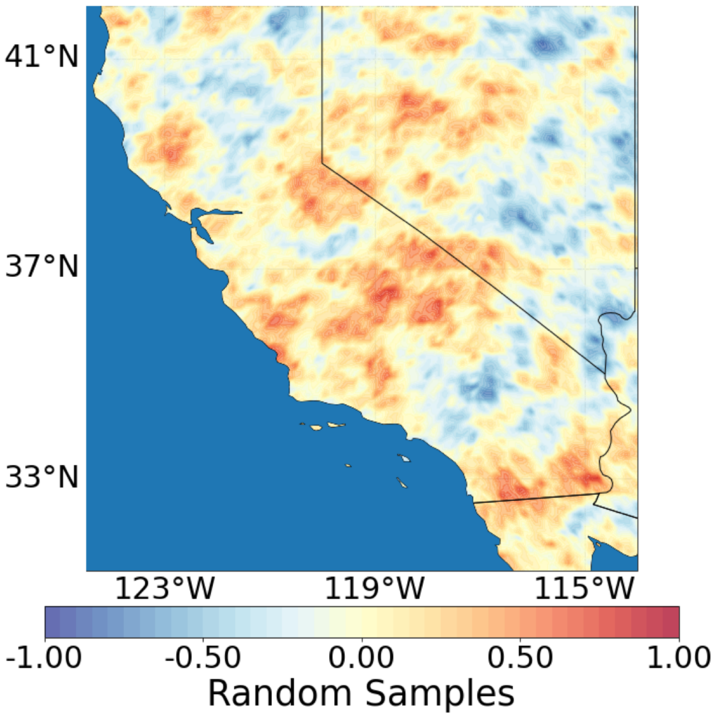
- Imposes the spatial variability on the non-ergodic coefficients:
  - type of correlation
  - length scale
  - size

$$\delta c \sim N\left(\mu(\vec{t}), \kappa(\vec{t}, \vec{t})\right)$$

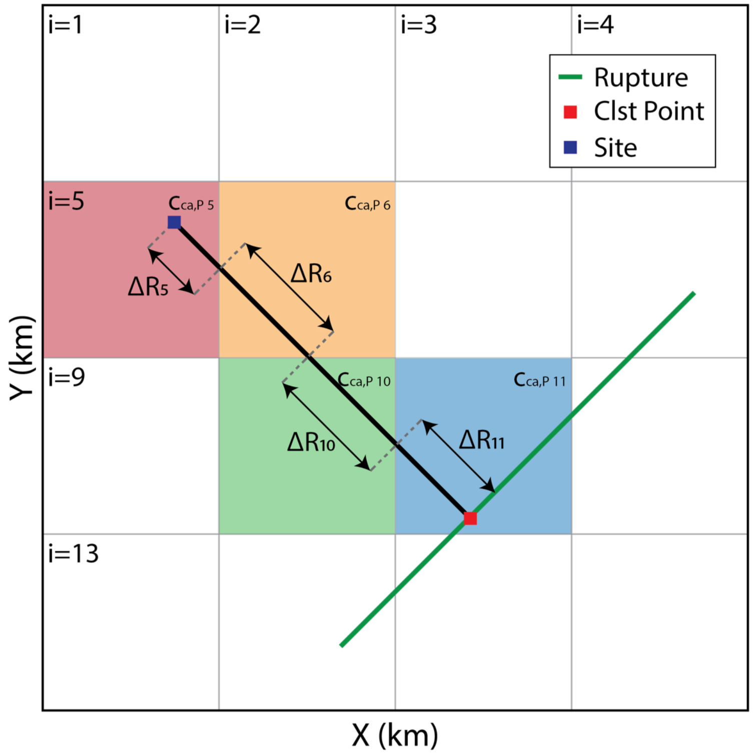
Mean Function

Kernel Function (Controls spatial correlation)





Cell Specific Anelastic Attenuation



Cell specific anelastic attenuation

$$f_{atten,P} = c_{ca,P\ 11}\ \Delta R_{11} + c_{ca,P\ 10}\ \Delta R_{10}$$
$$c_{ca,P\ 6}\ \Delta R_{6} + c_{ca,P\ 5}\ \Delta R_{5}$$

Anelastic Attenuation:

$$f_{atten,P} = \Delta\vec{R} \cdot \vec{c}_{ca,P}$$

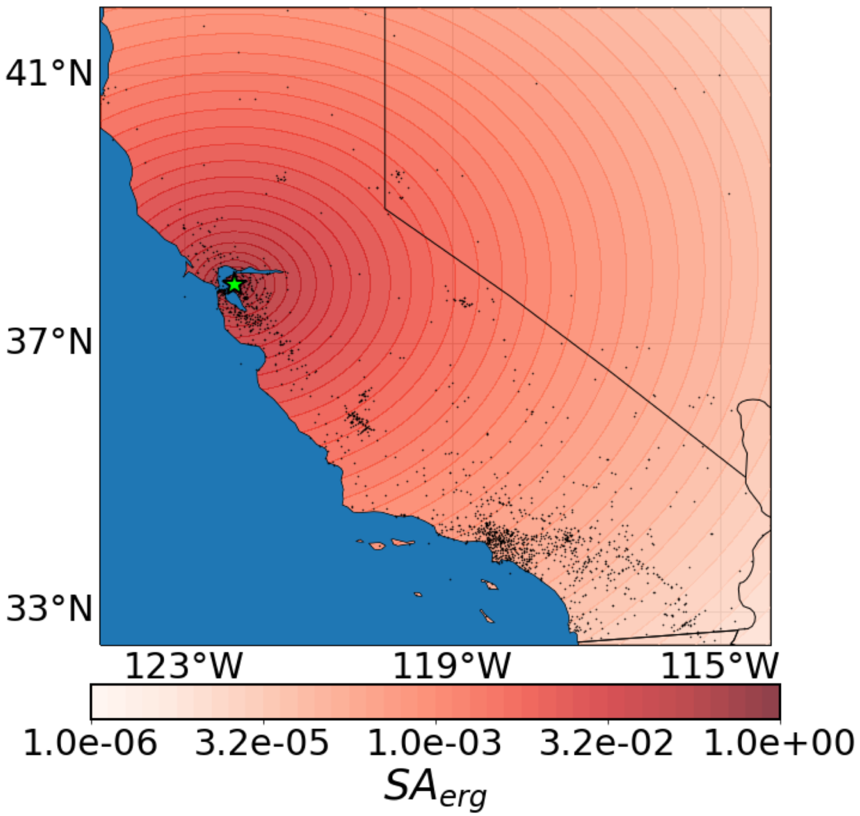
Cell path segments

Cell attenuation coefficients

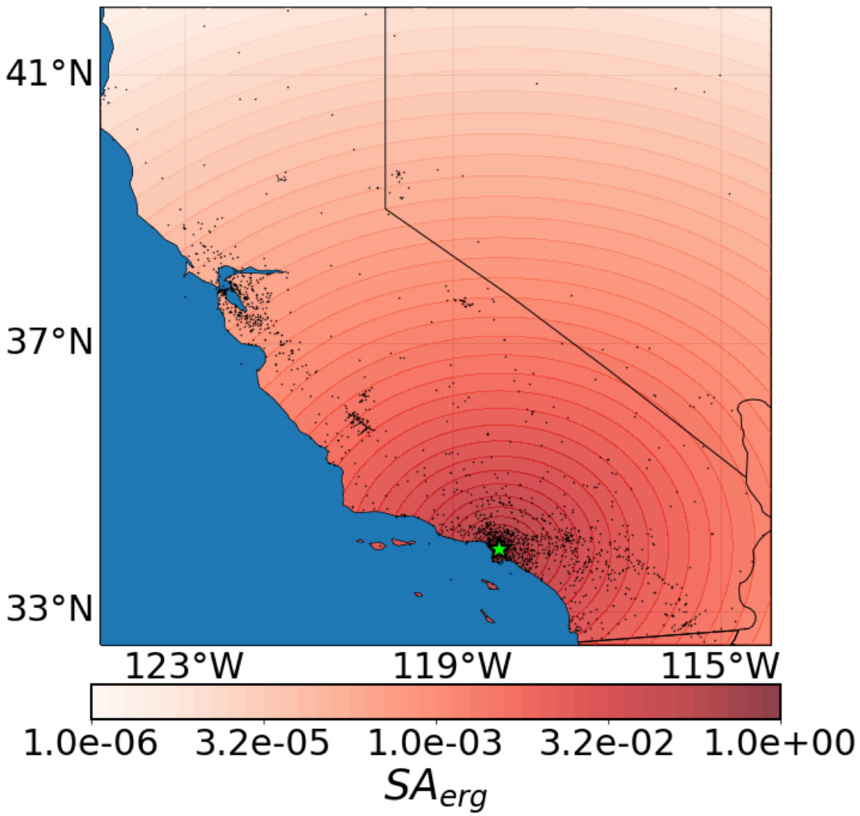
Fully non-ergodic GMM

$$f_{nerg}(M, R_{rup}, \ldots, t_E, t_S) = f_{erg}(M, R_{rup}, \ldots) +$$
$$\delta c_{1,E}(t_E) + \delta c_{1,S}(t_S) +$$
$$\Delta\vec{R} \cdot \vec{c}_{ca,P} - c_{a,erg} R_{rup}$$

Ergodic Ground Motion Models

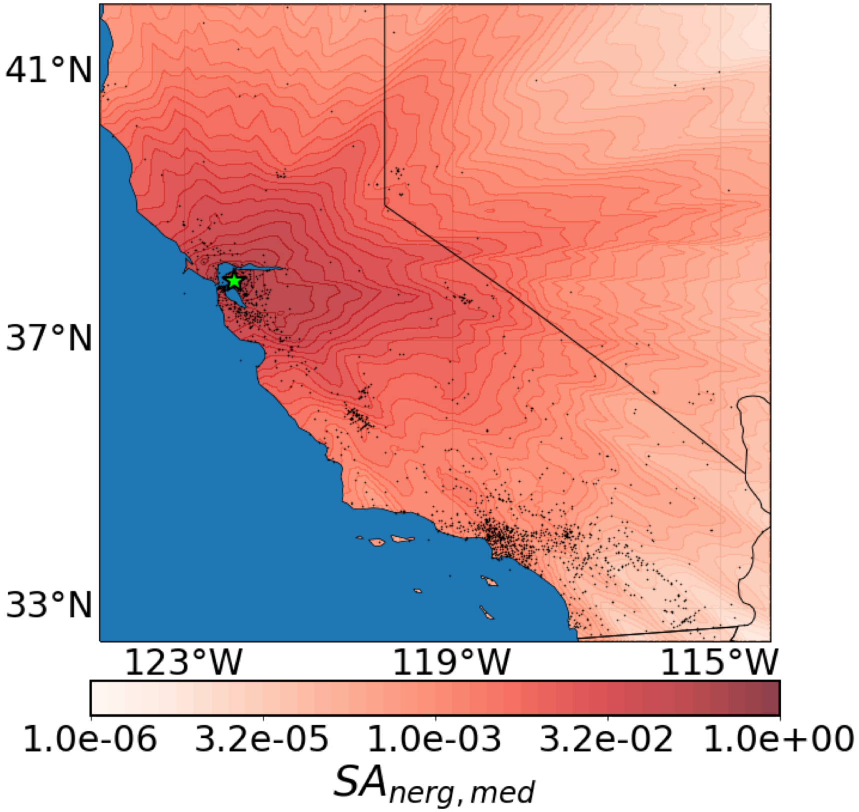


Earthquake in Bay Area

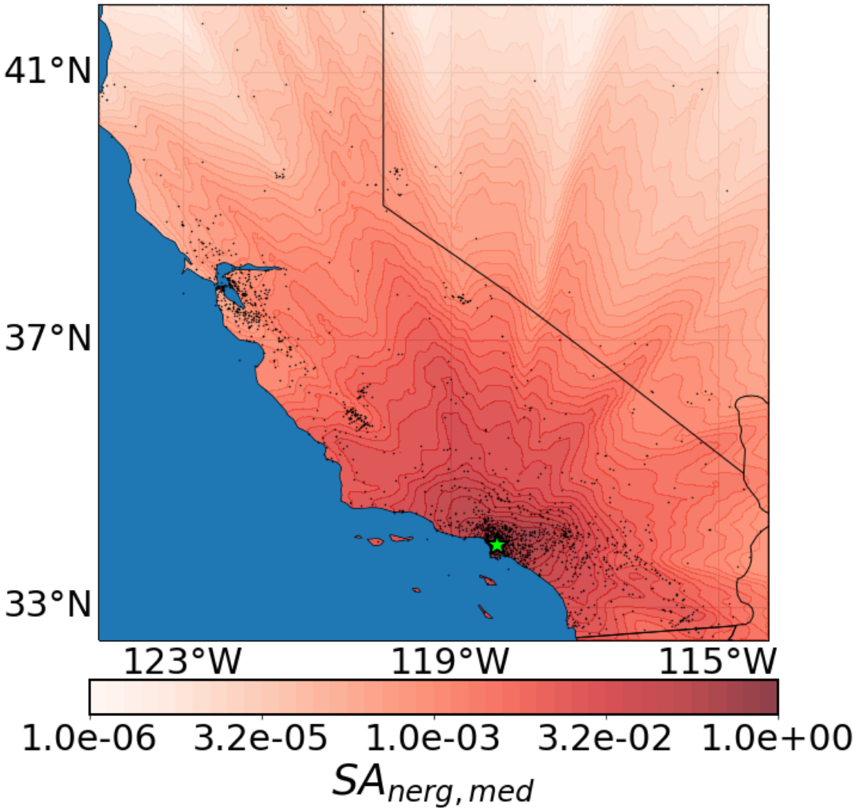


Earthquake in Los Angeles

Nonergodic Ground Motion Models



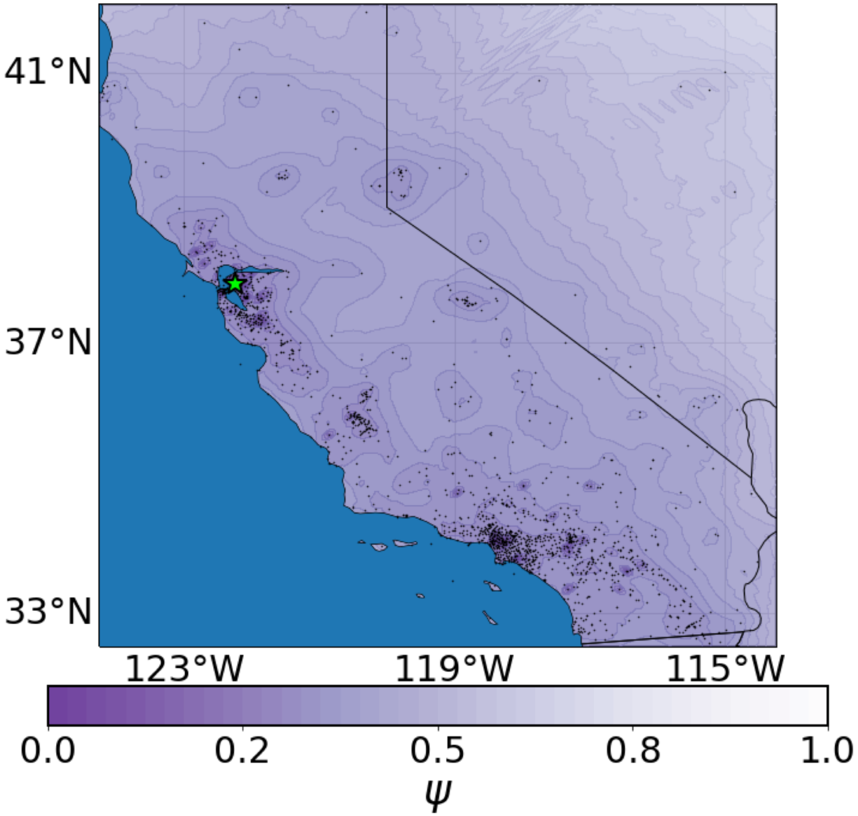
Median non-ergodic GM for
Earthquake in Bay Area



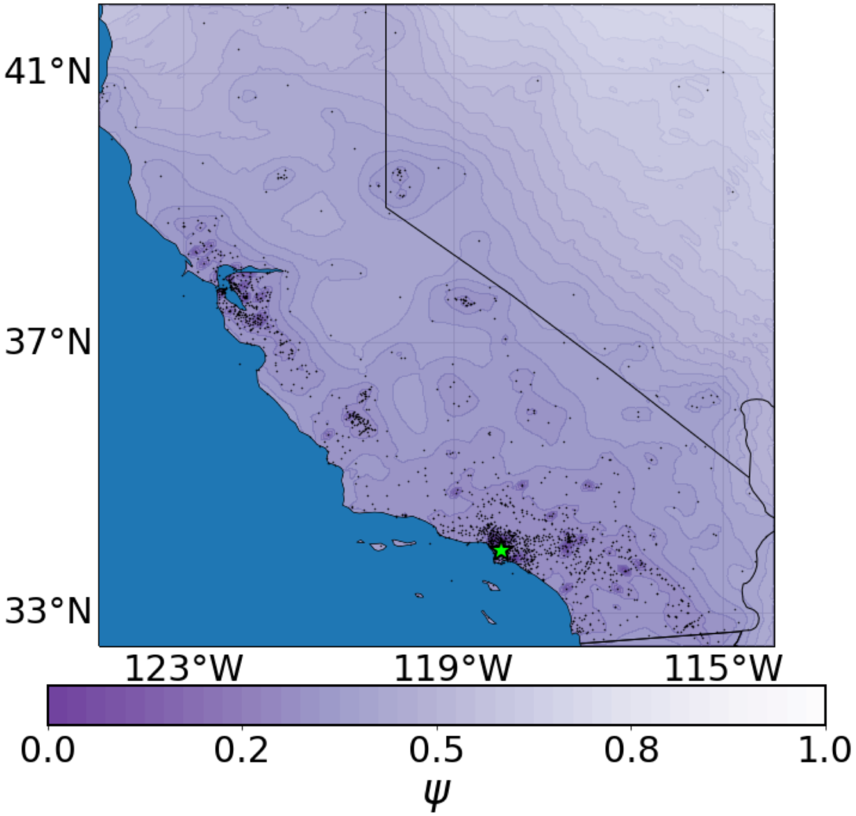
Median non-ergodic GM for
Earthquake in Los Angeles

Nonergodic Ground Motion Models

- In regions with limited data, the systematic effects are unknown

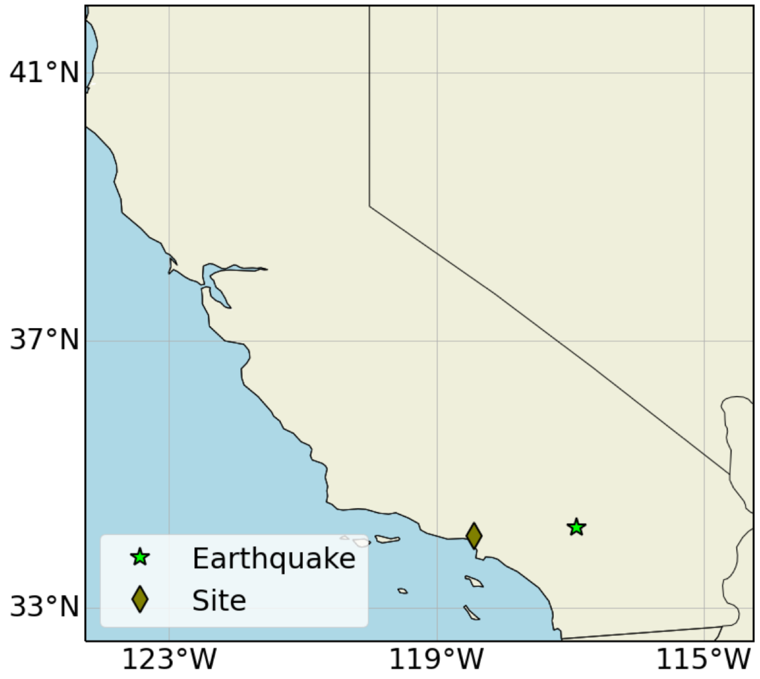


Epistemic Uncertainty for
Earthquake in Bay Area



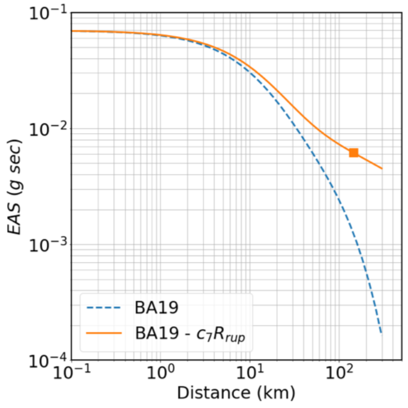
Epistemic Uncertainty for
Earthquake in Los Angeles

Prediction

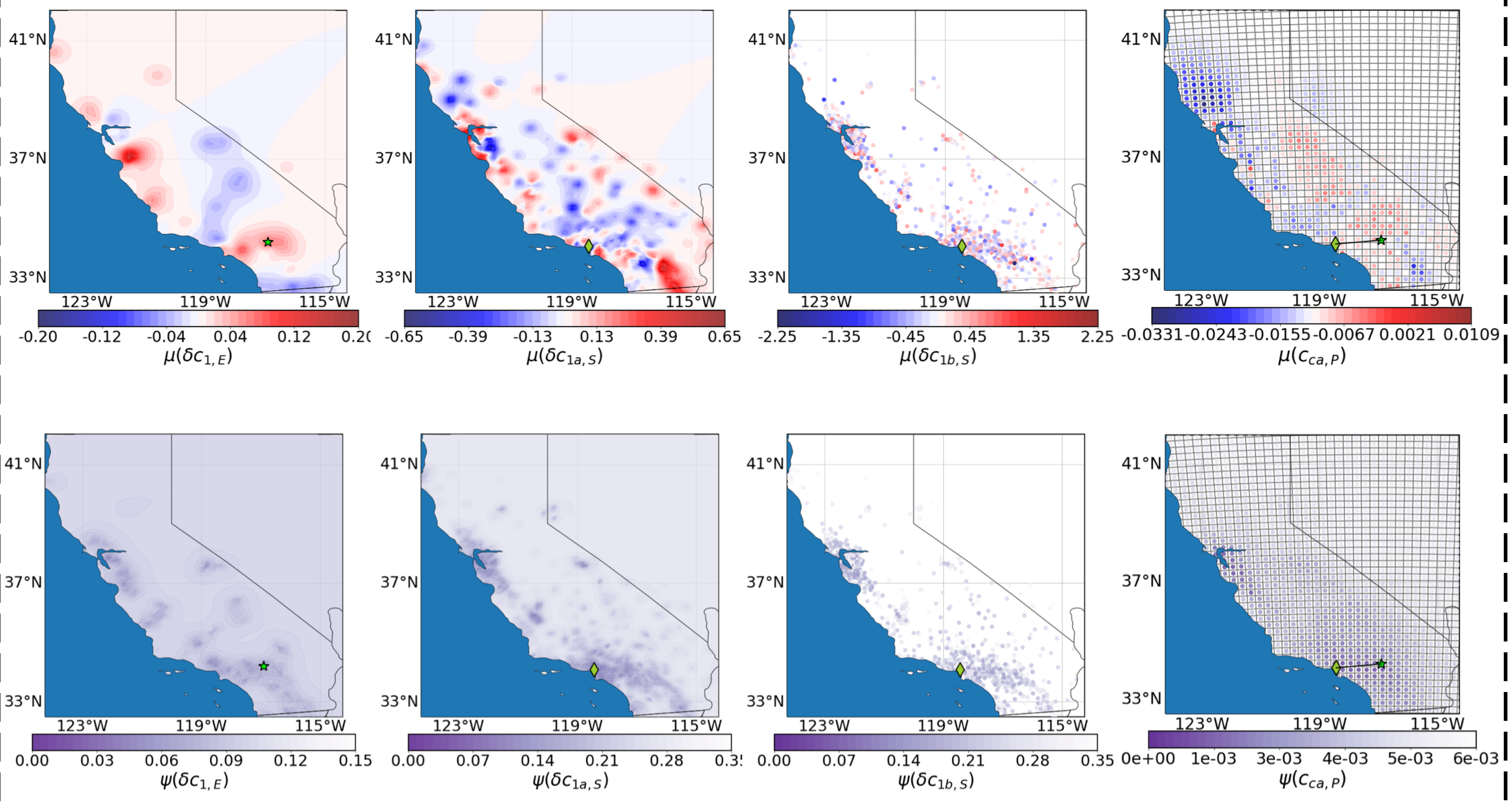


Source & Site location

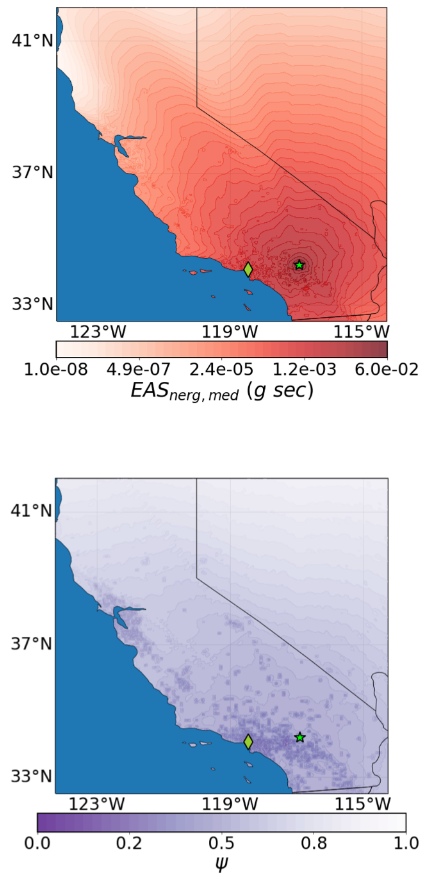
Median Scaling



Non-ergodic Effects



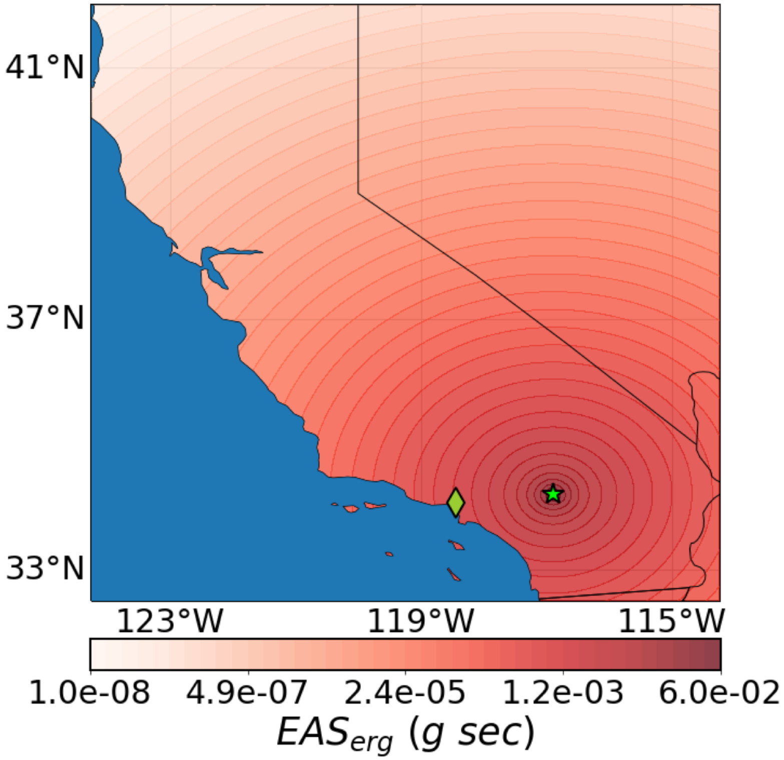
Non-ergodic Predictions



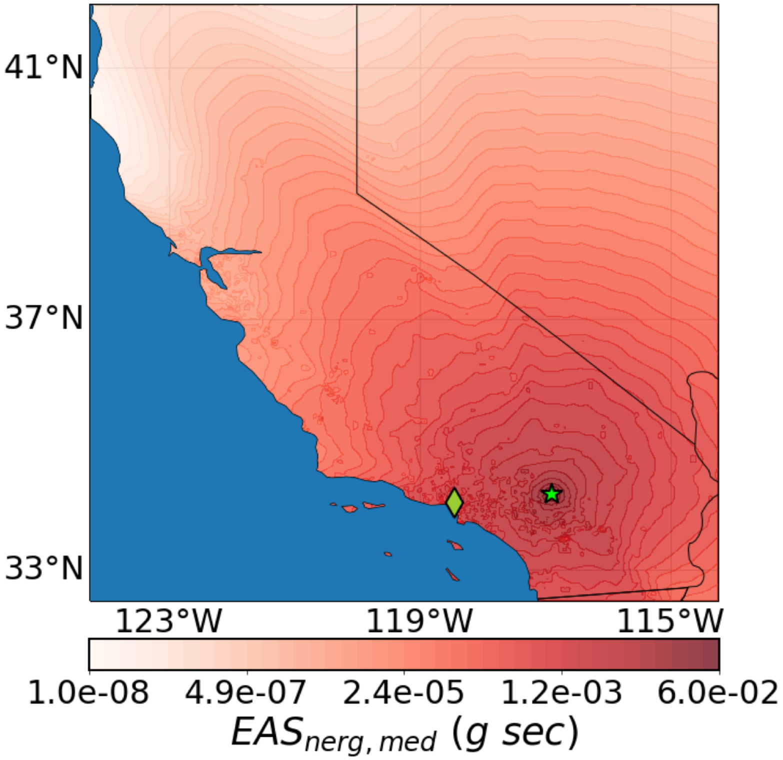
$$EAS_{erg} \times \exp(\ \delta c_{1,E}(t_E) + \delta c_{1a,S}(t_S) + \delta c_{1b,S}(t_S) + c_{ca,P}(t_C) \cdot \Delta \vec{R}) = EAS_{nerg}$$

Ergodic Prediction

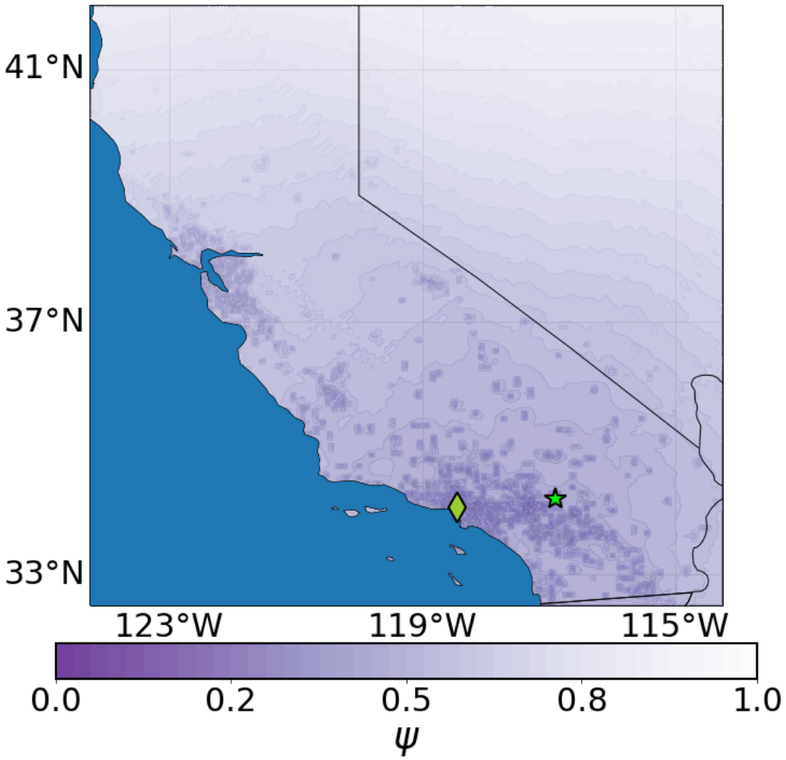
Nonergodic Prediction



Median Ergodic Prediction



Median Nonergodic Prediction



Epistemic Uncertainty of Nonergodic Prediction