The Prediction Problems of Earthquake System Science

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GSA Lecture

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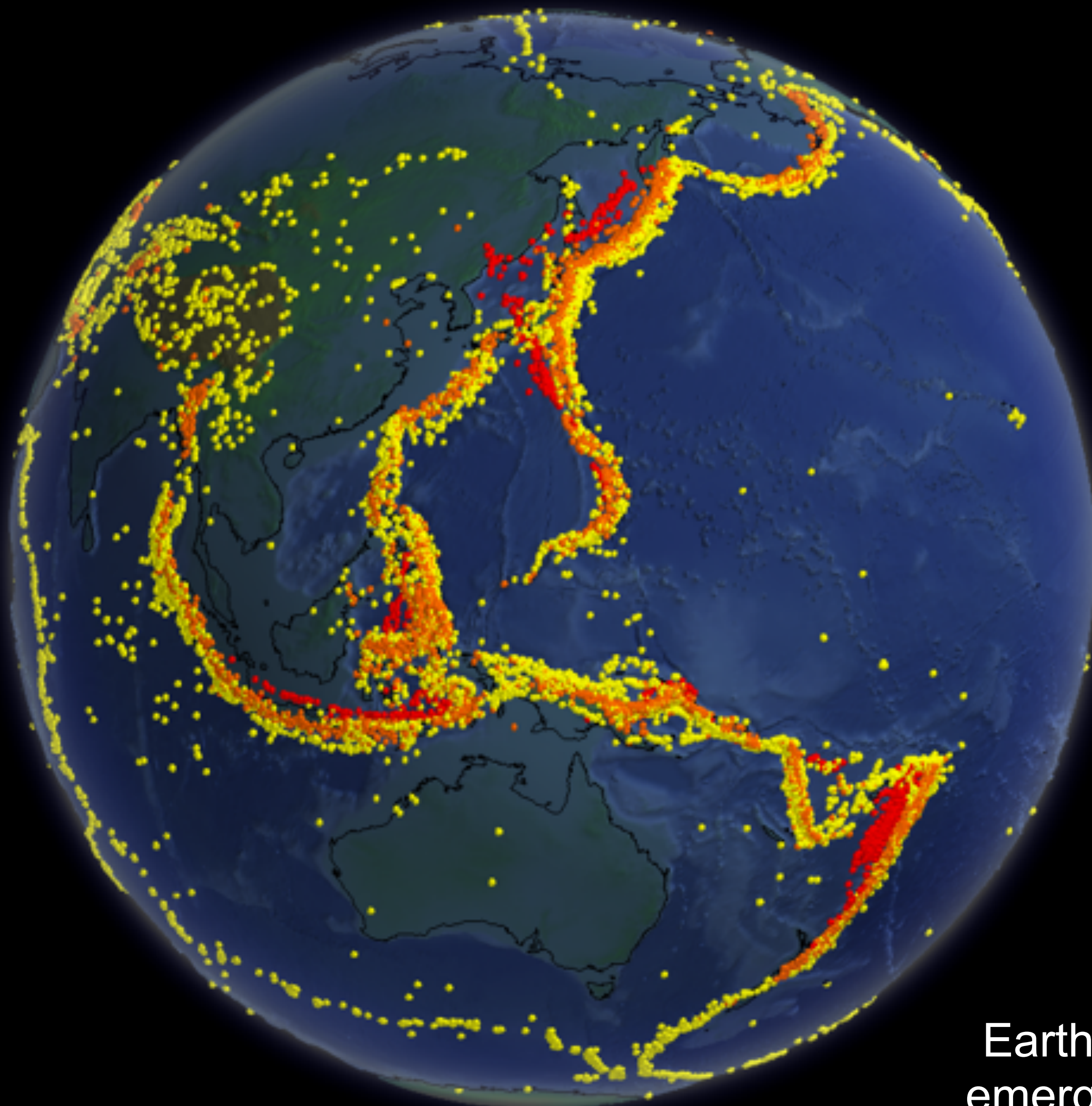
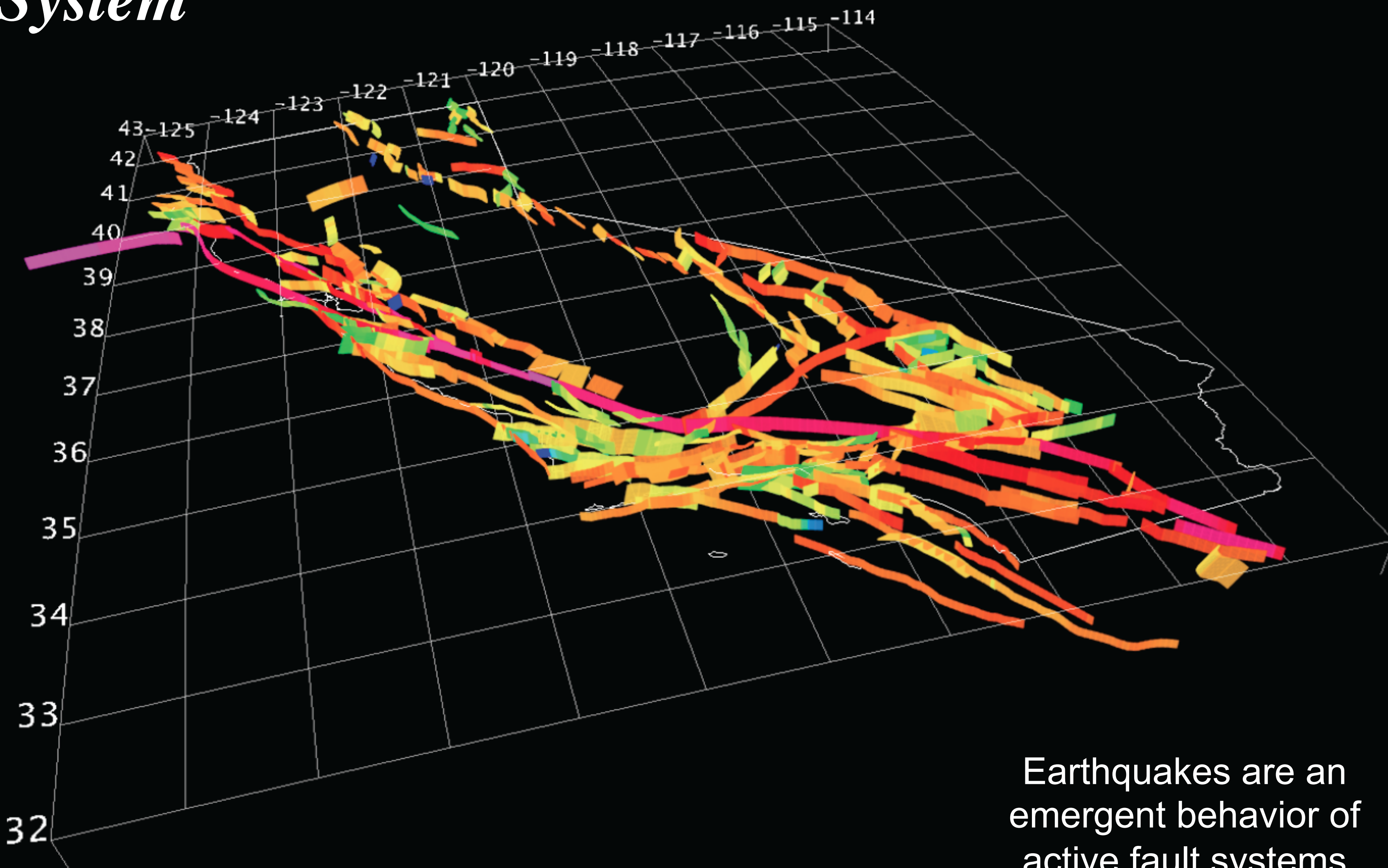
Earthquake Systems



Earthquakes are an emergent behavior of active fault systems

San Andreas System



Earthquakes are an emergent behavior of active fault systems

Earthquake System Science

- **Earthquake systems**
  - **Models of active fault systems that predict earthquake behaviors**
- **Earthquake behaviors of societal interest**
  - **Fault rupture**
  - **Ground shaking** ← *focus of this presentation*
  - **Tsunami**
  - **Liquefaction, landsliding, and other secondary effects**
- **Fundamental prediction problem of earthquake system science**
  - **Provide *prospective* information about these behaviors useful in reducing earthquake risks and preparing for earthquake disasters**

Fundamental Prediction Problem

Provide information about future ground motions useful in reducing earthquake risks and preparing for earthquake disasters

- **Two main approaches:**

  1. ***Deterministic short-term prediction:*** **"Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA <u>during the next month.</u>"**

  2. ***Probabilistic long-term forecasting:*** **"Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA <u>with a 2% probability in the next 50 year</u>s."**

Two Approaches to Earthquake Prediction

Deterministic Earthquake Prediction

"Silver-Bullet Approach"

- **Search for *diagnostic precursory signals* that can predict the location, time, and magnitude of an impending event with high probability and low error rates (false alarms and failures-to-predict)**

x *Has not yet produced a reliable method for short-term deterministic prediction*

Probabilistic Earthquake Forecasting

"Brick-by-Brick Approach"

- **Build *system-specific models* of earthquake recurrence, stress evolution, and triggering within the framework of probabilistic seismic hazard analysis (PSHA)**

✓ *Has produced reliable methods for long-term and short-term probabilistic forecasting*

Fundamental Prediction Problem

Provide information about future ground motions useful in reducing earthquake risks and preparing for earthquake disasters

1. ***Deterministic short-term prediction:*** **"Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA <u>during the next month.</u>"**
2. ***Probabilistic long-term forecasting:*** **"Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA <u>with a 2% probability in the next 50 years</u>."**

- **Replace the first with:**

3. ***Probabilistic short-term forecasting:*** **"Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA <u>with a 2% probability in the next month</u>."**

- **In this example, the short-term probability gain is the ratio**

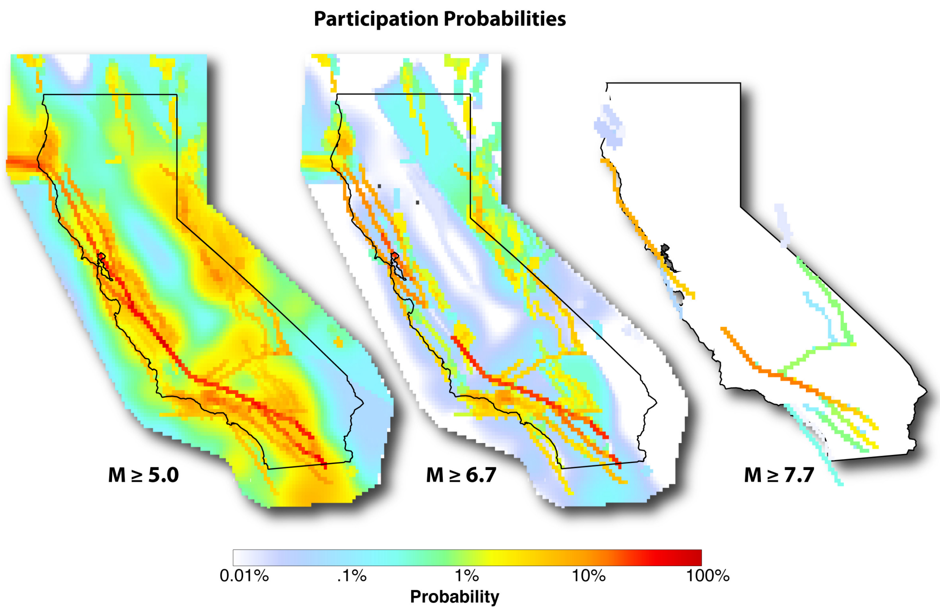
***50 yrs ÷ 1 month* = 600**

  - **Should short-term forecasts with high-gain but low-probability be disseminated to the public?**

Outline

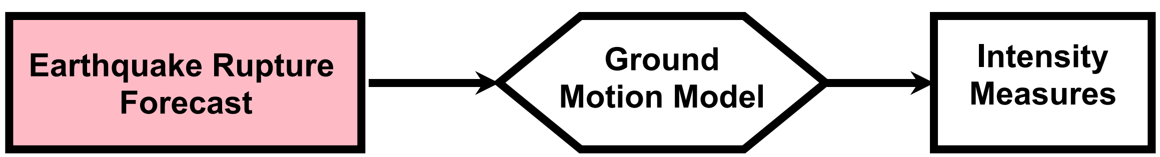
- **Probabilistic Seismic Hazard Analysis**
  - Concepts of aleatory variability and epistemic uncertainty
- **Long-term earthquake rupture forecasting**
  - Uniform California Earthquake Rupture Forecast (UCERF3)
- **Ground motion prediction**
  - CyberShake physics-based hazard model
- **Short-term earthquake forecasting**
  - Operational earthquake forecasting
- **Future of physics-based earthquake forecasting**
  - Earthquake rupture simulators

Probabilistic Seismic Hazard Model



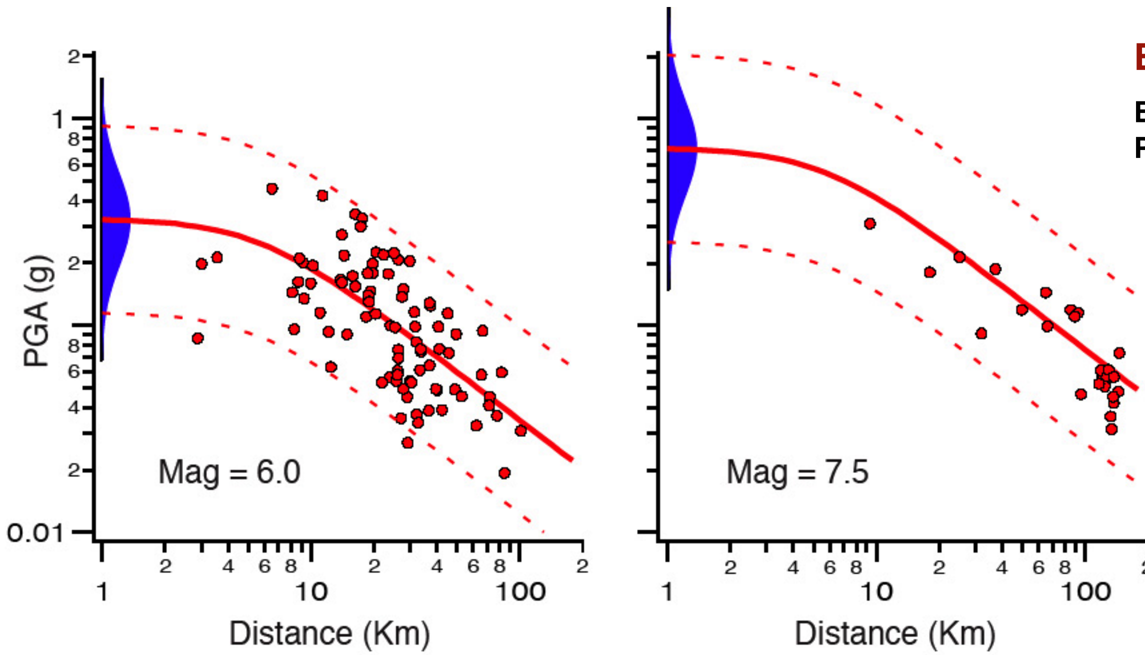
Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)



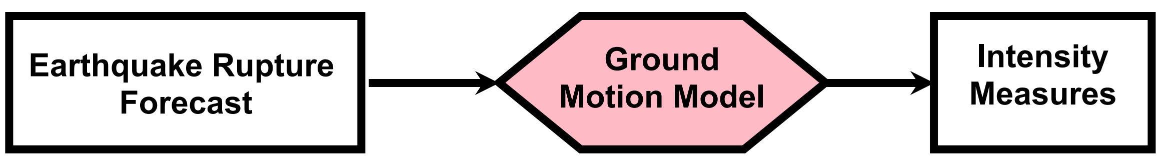
$P(S_k)$ $\qquad$ $P(Y_n \mid S_k)$ $\qquad$ $P(Y_n)$

Probabilistic Seismic Hazard Model



Boore et al. (1997)

Empirical Ground Motion Prediction Equations (GMPEs)

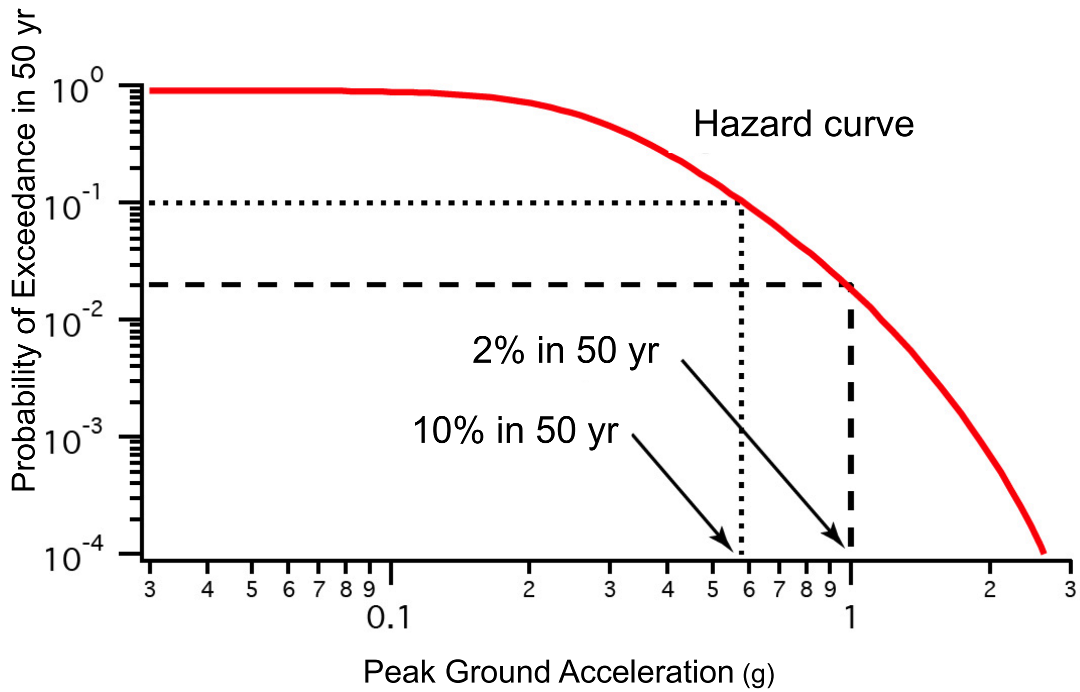


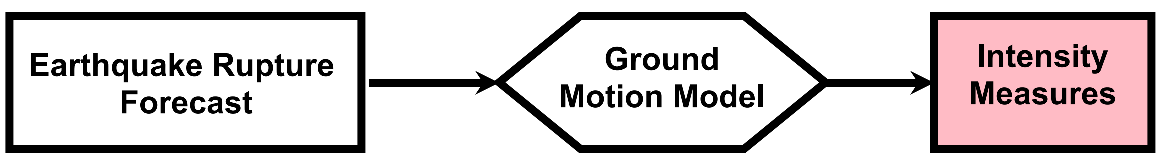
$P(S_k)$ $\quad$ $P(Y_n \mid S_k)$ $\quad$ $P(Y_n)$

Probabilistic Seismic Hazard Model

Hazard Curve:

- **Shaking intensity: Peak Ground Acceleration (PGA)**
- **Interval: 50 years**
- **Site: Downtown LA**



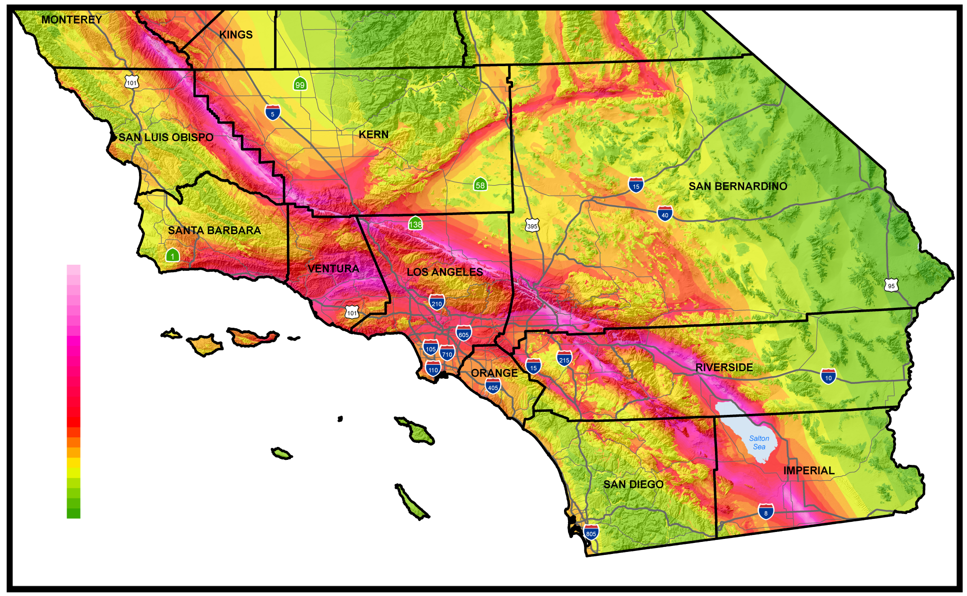


$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Probabilistic Seismic Hazard Model

National Seismic Hazard Map

PGA (%g) with 2% Probability of Exceedance in 50 years

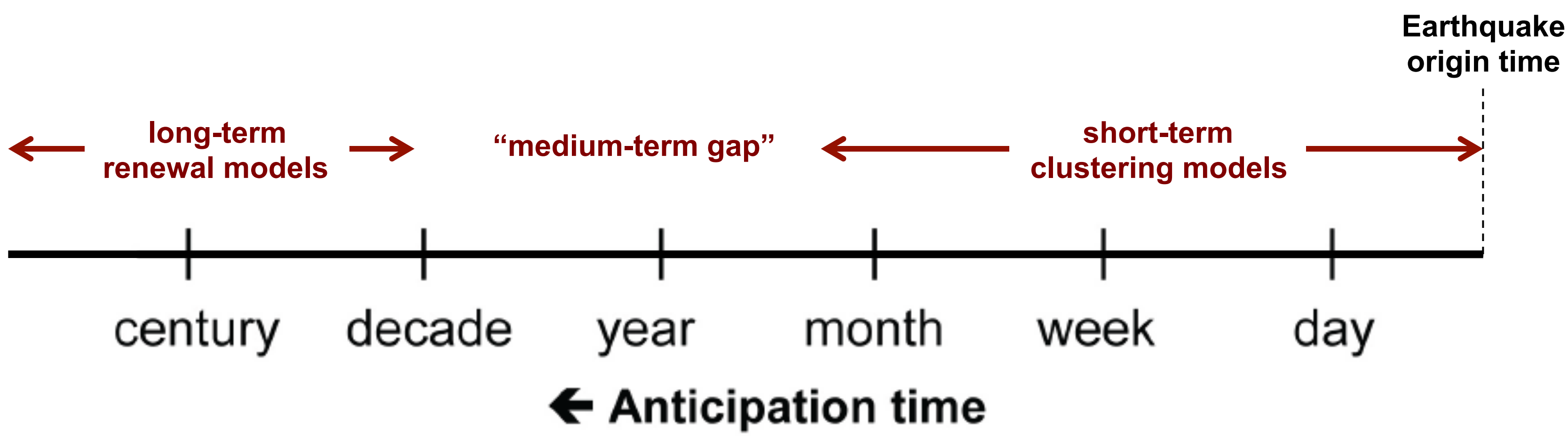


Earthquake Rupture Forecast → **Ground Motion Model** → **Intensity Measures**

$P(S_k)$ $\qquad$ $P(Y_n \mid S_k)$ $\qquad$ $P(Y_n)$

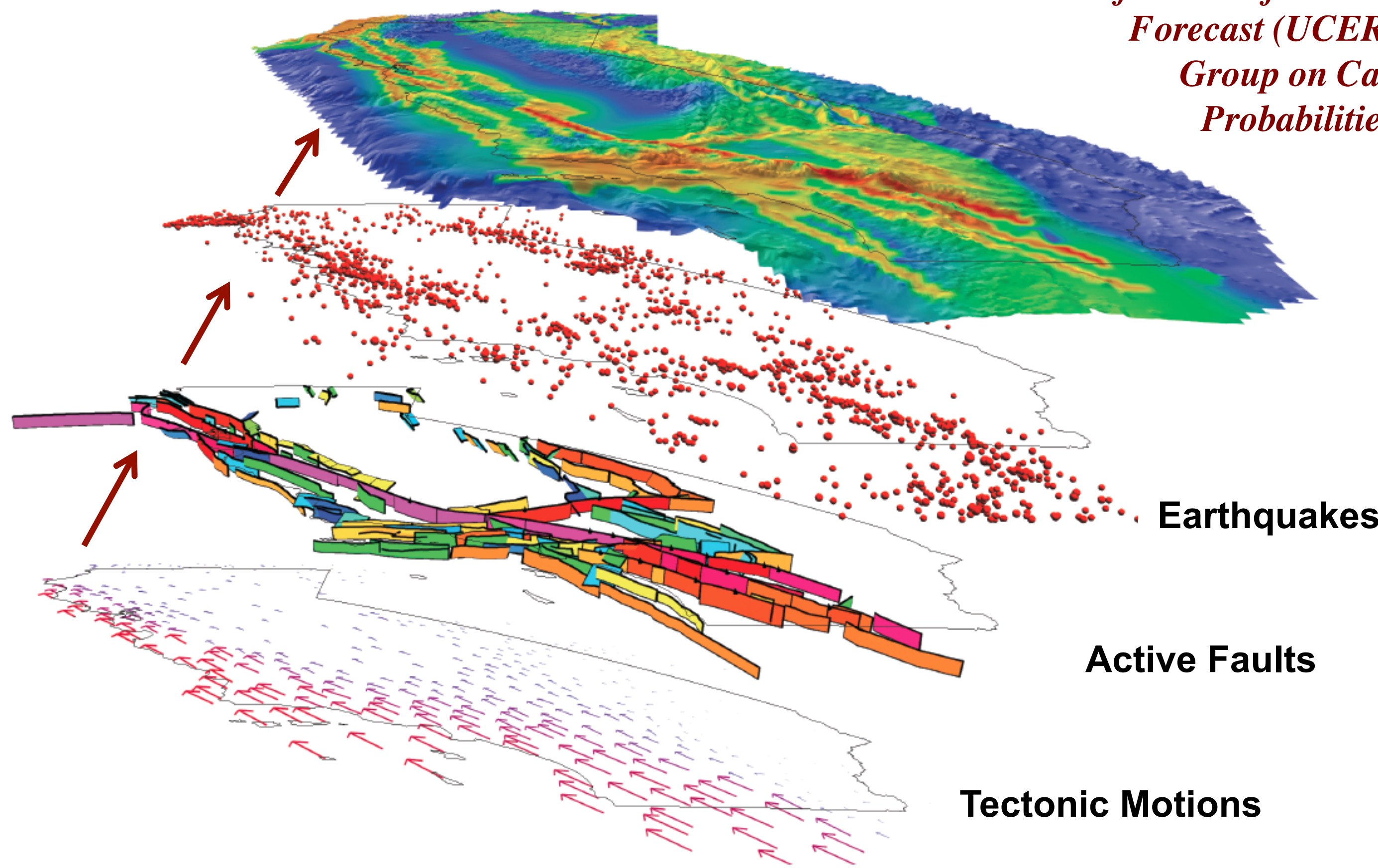
Scales of Seismic Hazard Change

- **Faults accumulate stress over centuries during quasi-static tectonic loading**
  - **stress cycle represented by Reid *renewal* models**
- **Faults redistribute stress in seconds during dynamic ruptures**
  - **earthquake sequences represented by Omori-Utsu *clustering* models**
- **These two types of models are statistically opposed**
  - **“medium-term forecasting gap”**



Long-Term Forecasting Models

Uniform California Earthquake Rupture Forecast (UCERF3) by the Working Group on California Earthquake Probabilities (Field et al., 2014)



Fault Models

Specifies the spatial geometry of larger, more active faults.

Deformation Models

Provides fault slip rates used to calculate seismic moment release.

Eathquake-Rate Models

Gives the long-term rate of all possible damaging earthquakes throughout a region.

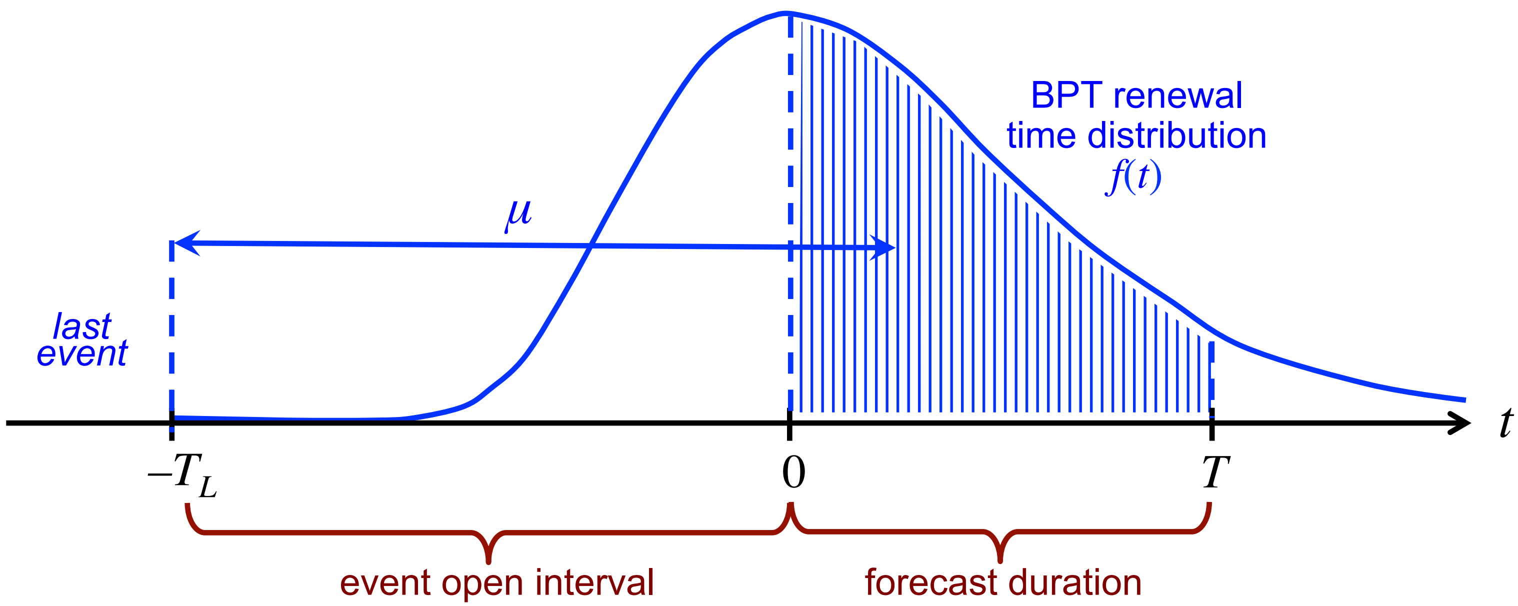
Probability Models

Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

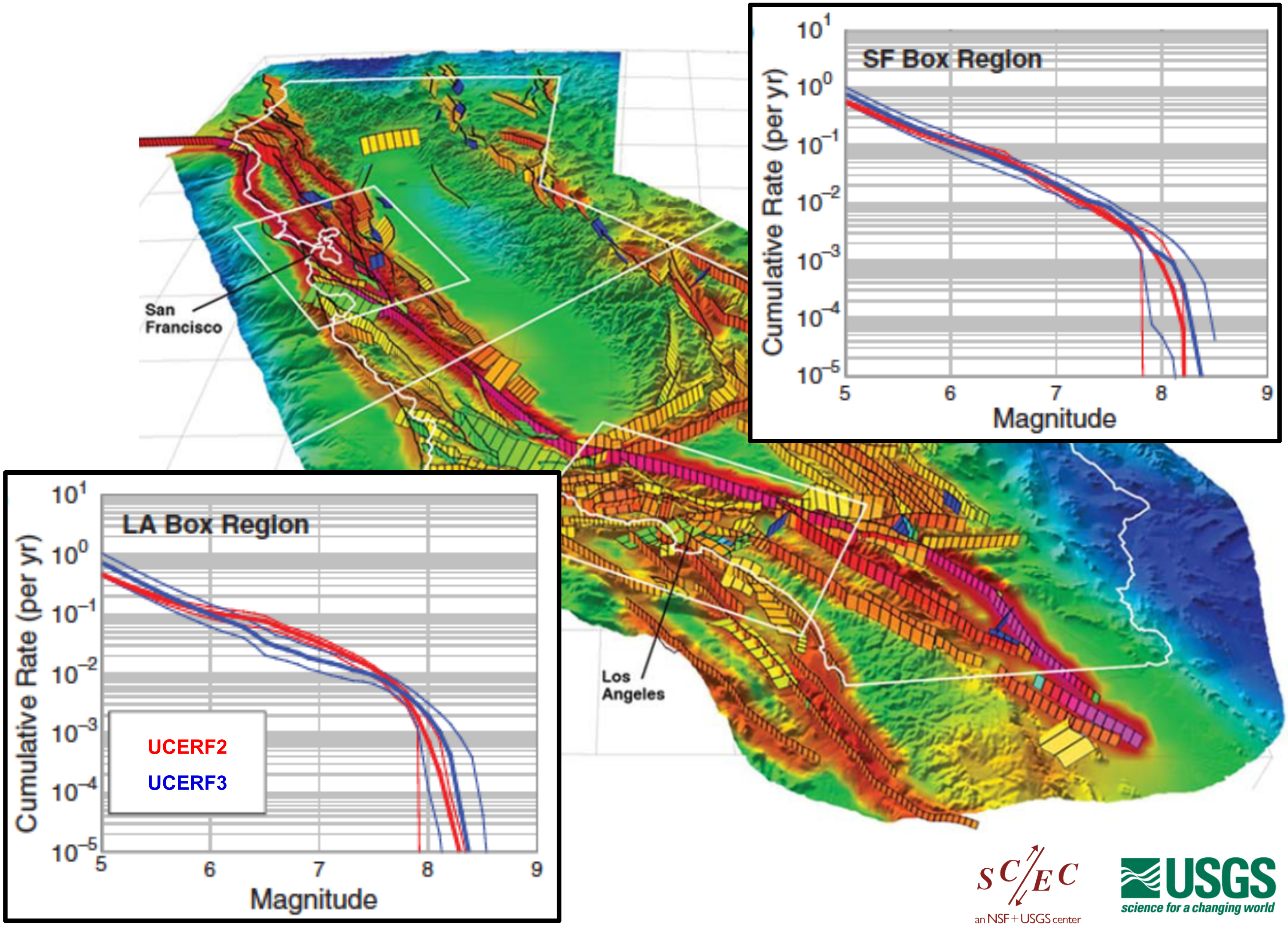
Long-Term Forecasting Models

Reid model: Characteristic earthquakes occur according to a renewal distribution set by time since last event T_L, the mean recurrence interval μ, and an aperiodicity α.

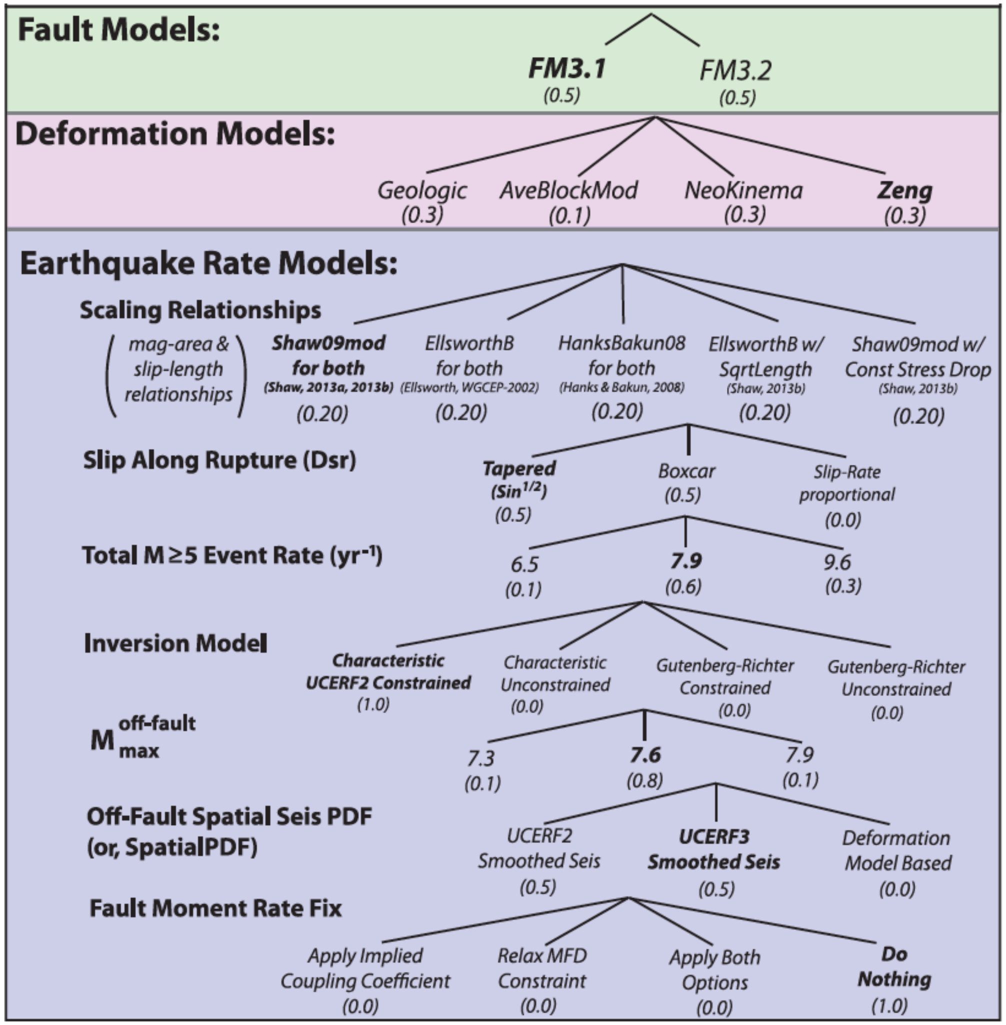
Example: Brownian Passage Time (BPT) renewal model



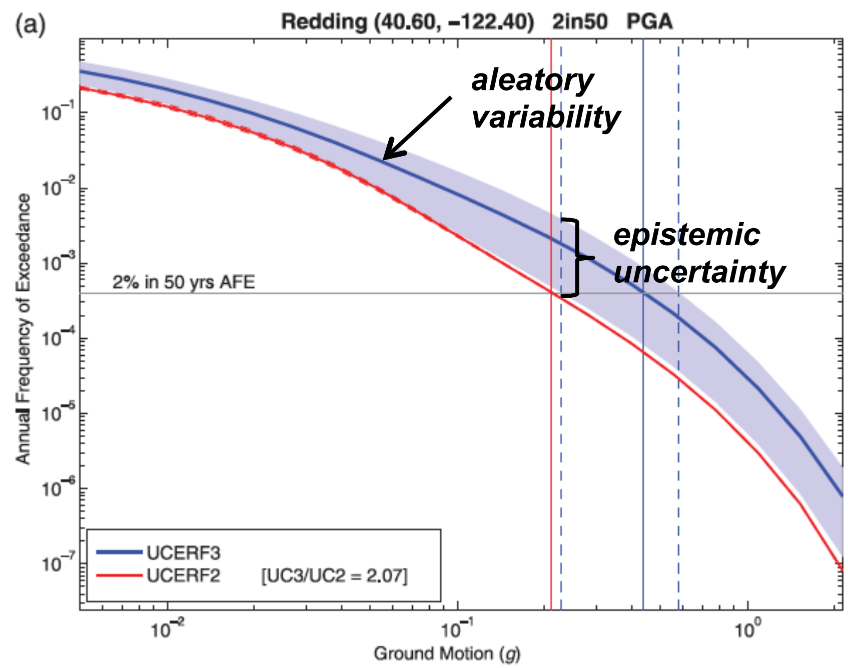
Long-Term Forecasting Models



Uncertainties in Earthquake Rupture Forecasts

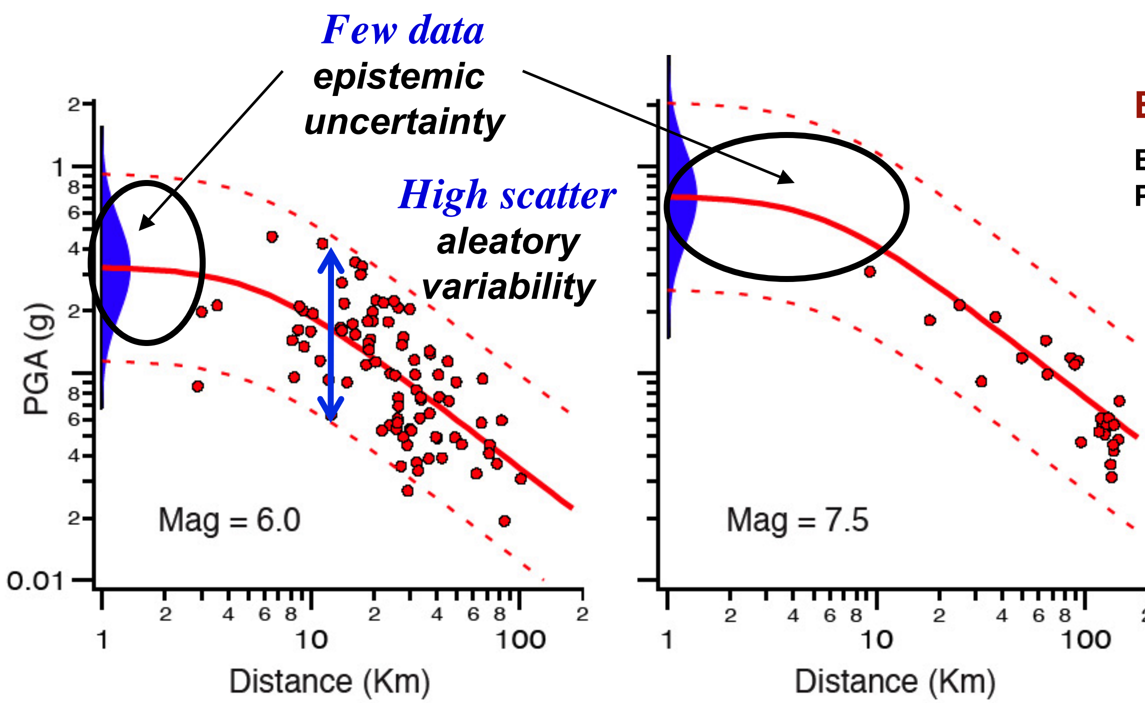


1440 branches express the epistemic uncertainties in the UCERF3 time-independent forecast



Comparison of UCERF2 and UCERF3 hazard curves at Redding CA

Uncertainties in Ground Motion Prediction Equations



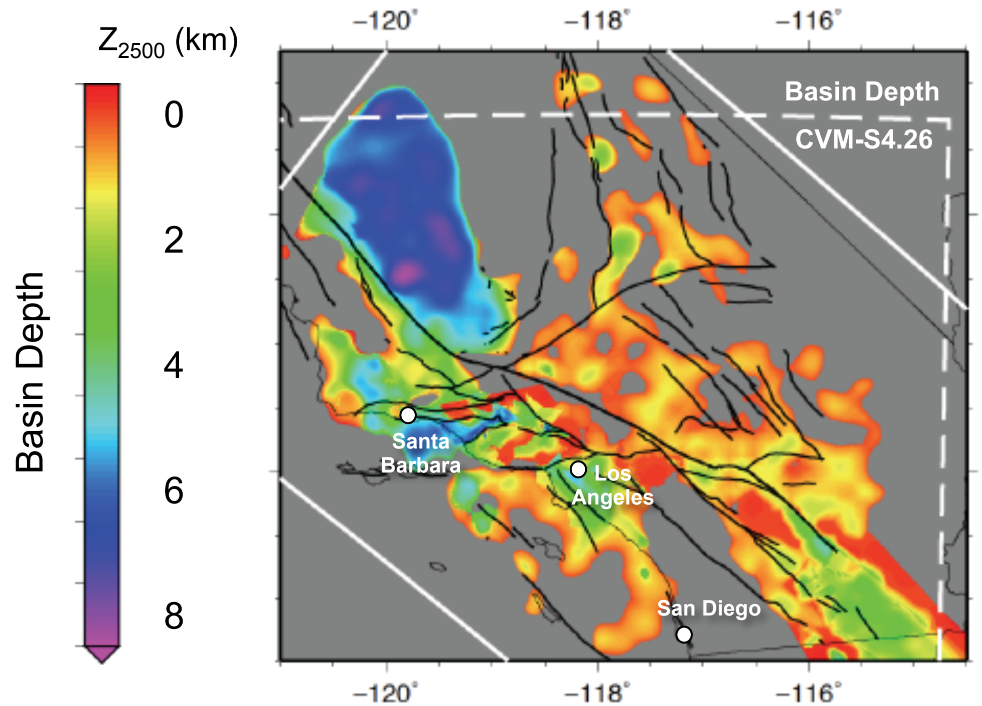
Boore et al. (1997)

Empirical Ground Motion Prediction Equations (GMPEs)

Earthquake Rupture Forecast → **Ground Motion Model** → **Intensity Measures**

$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Probabilistic Seismic Hazard Model

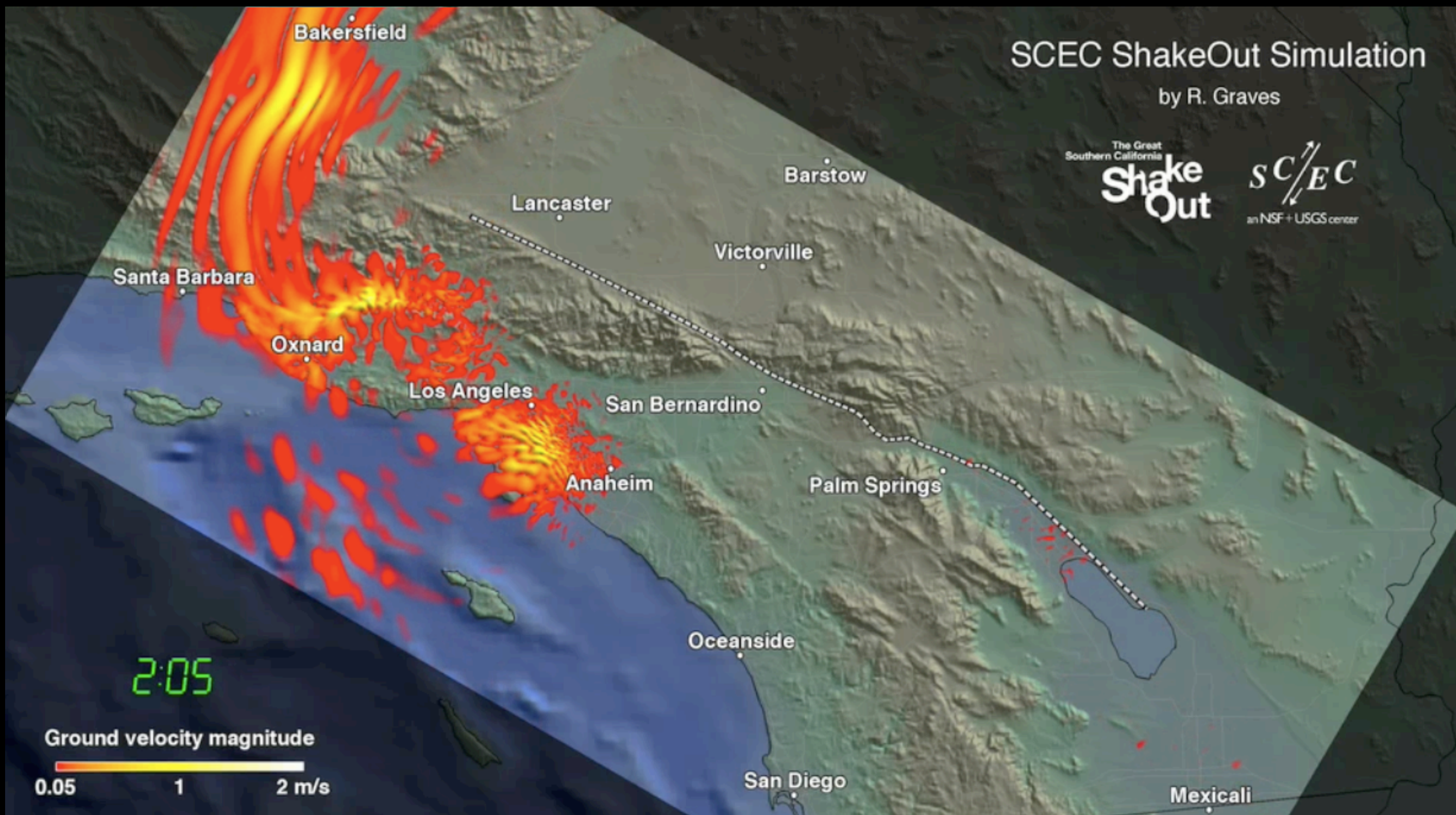


Much of the aleatory variability in the GMPEs comes from 3D heterogeneity in crustal structure

Earthquake Rupture Forecast → Ground Motion Model → Intensity Measures

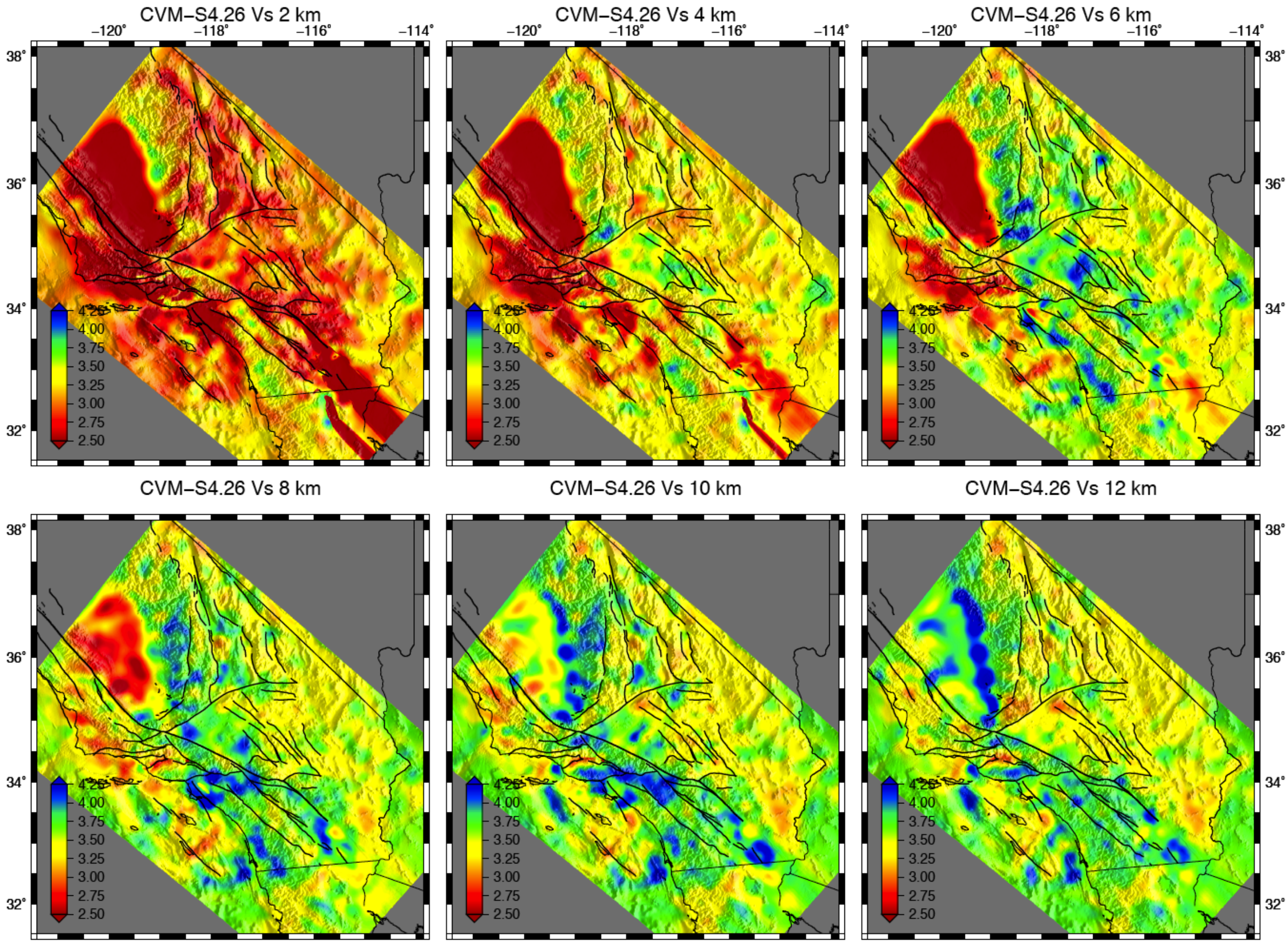
$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

ShakeOut Scenario
M7.8 Earthquake on Southern San Andreas Fault

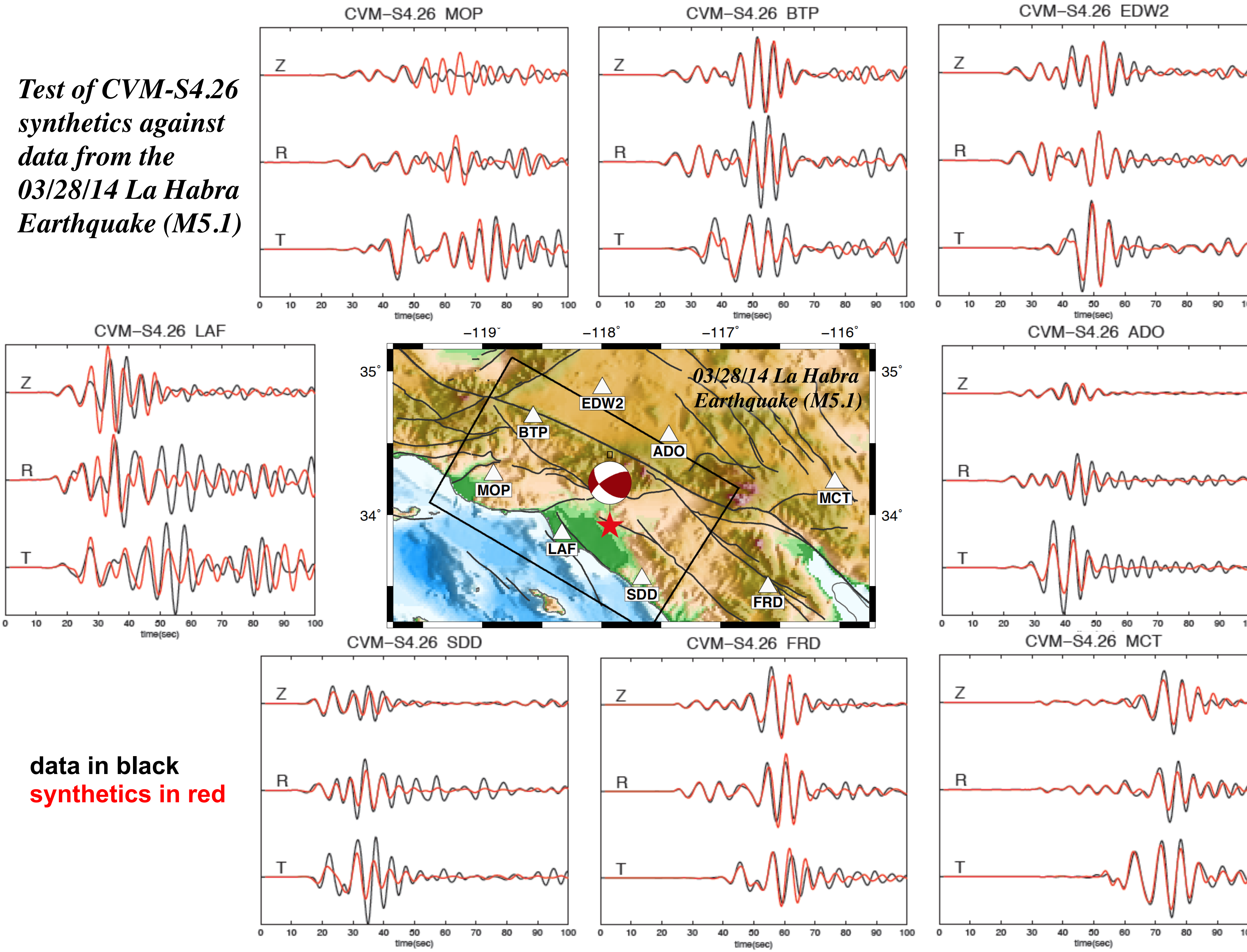


Full-3D Waveform Tomography

(Lee, Chen, Jordan, Maechling, Denolle & Beroza, JGR, 2014)

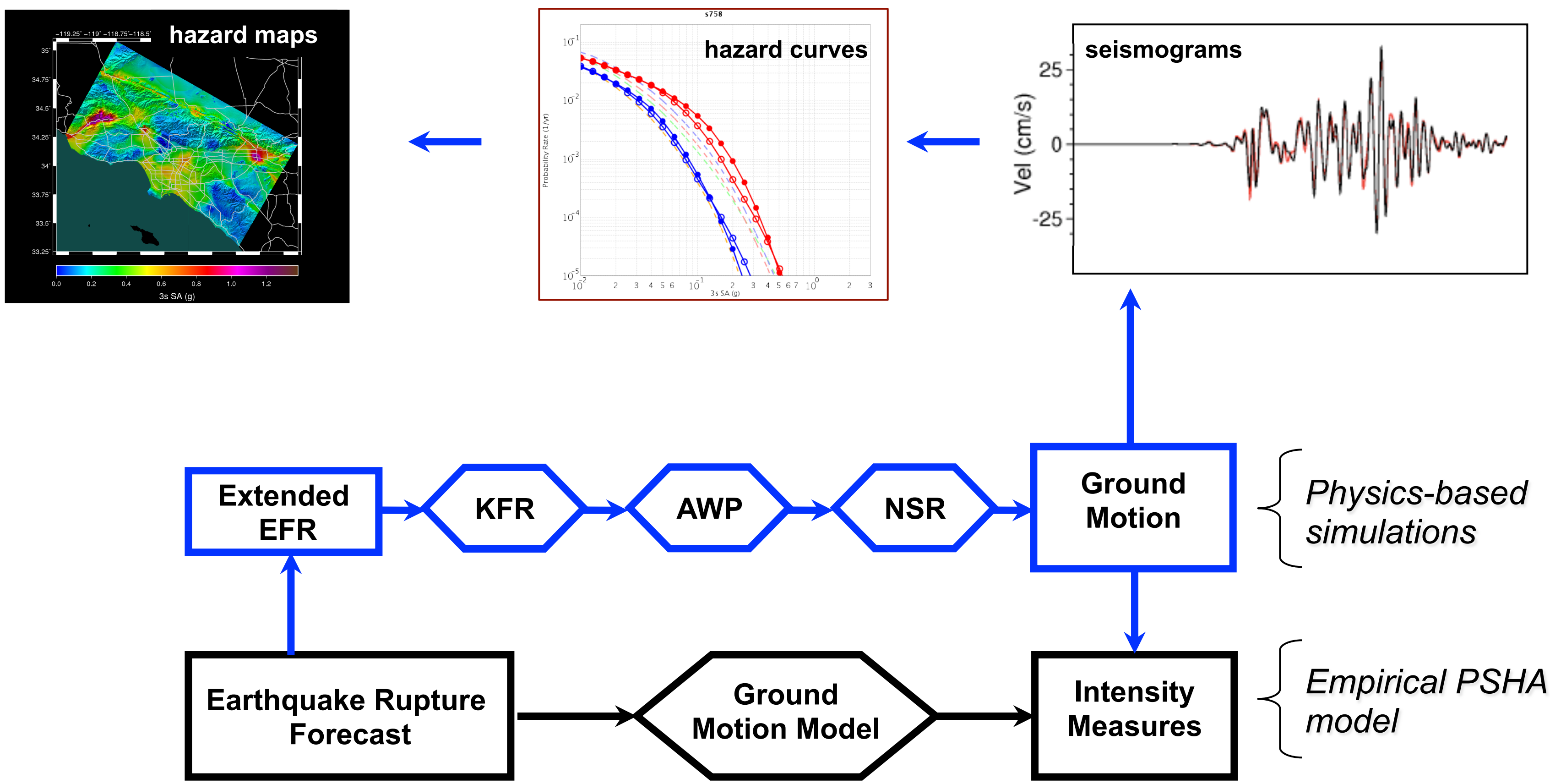


Test of CVM-S4.26 synthetics against data from the 03/28/14 La Habra Earthquake (M5.1)



data in black
synthetics in red

CyberShake Model: Physics-Based PSHA

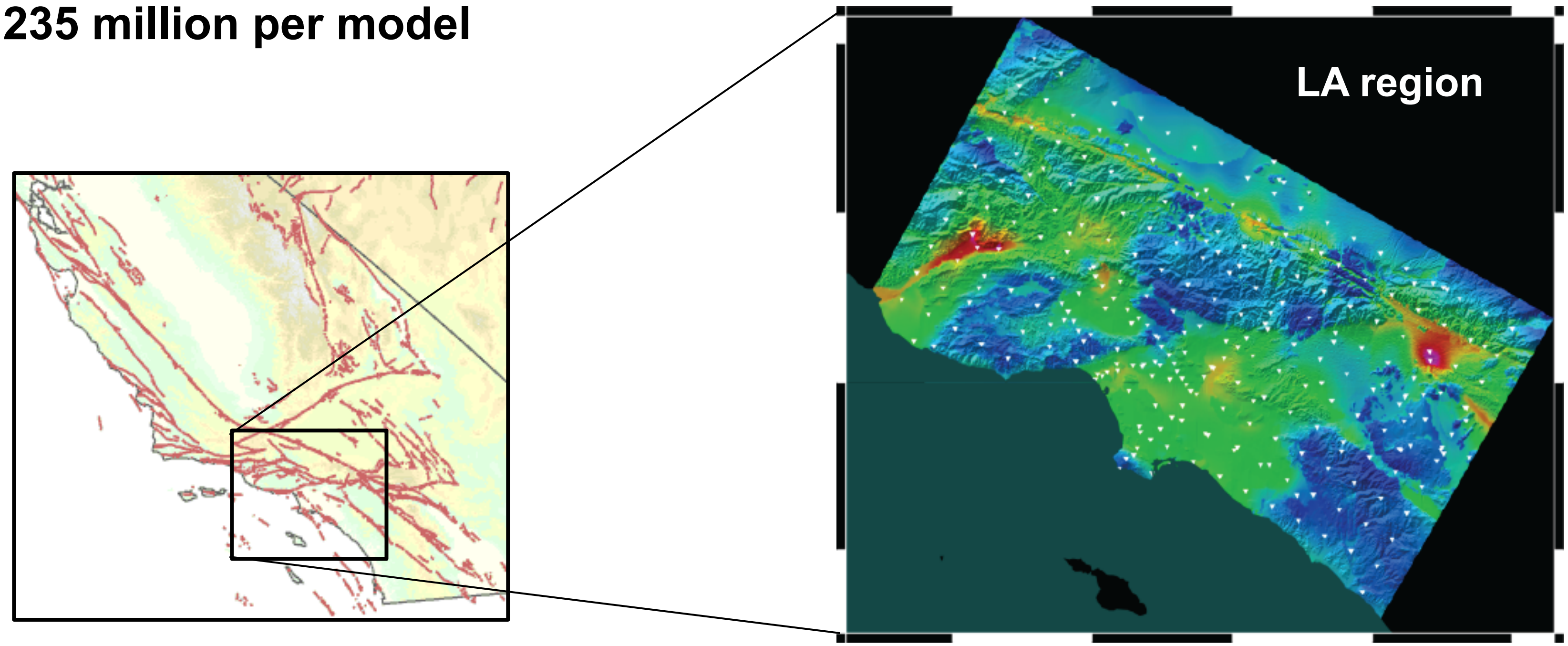


KFR = kinematic fault rupture model
AWP = anelastic wave propagation model
NSR = nonlinear site response

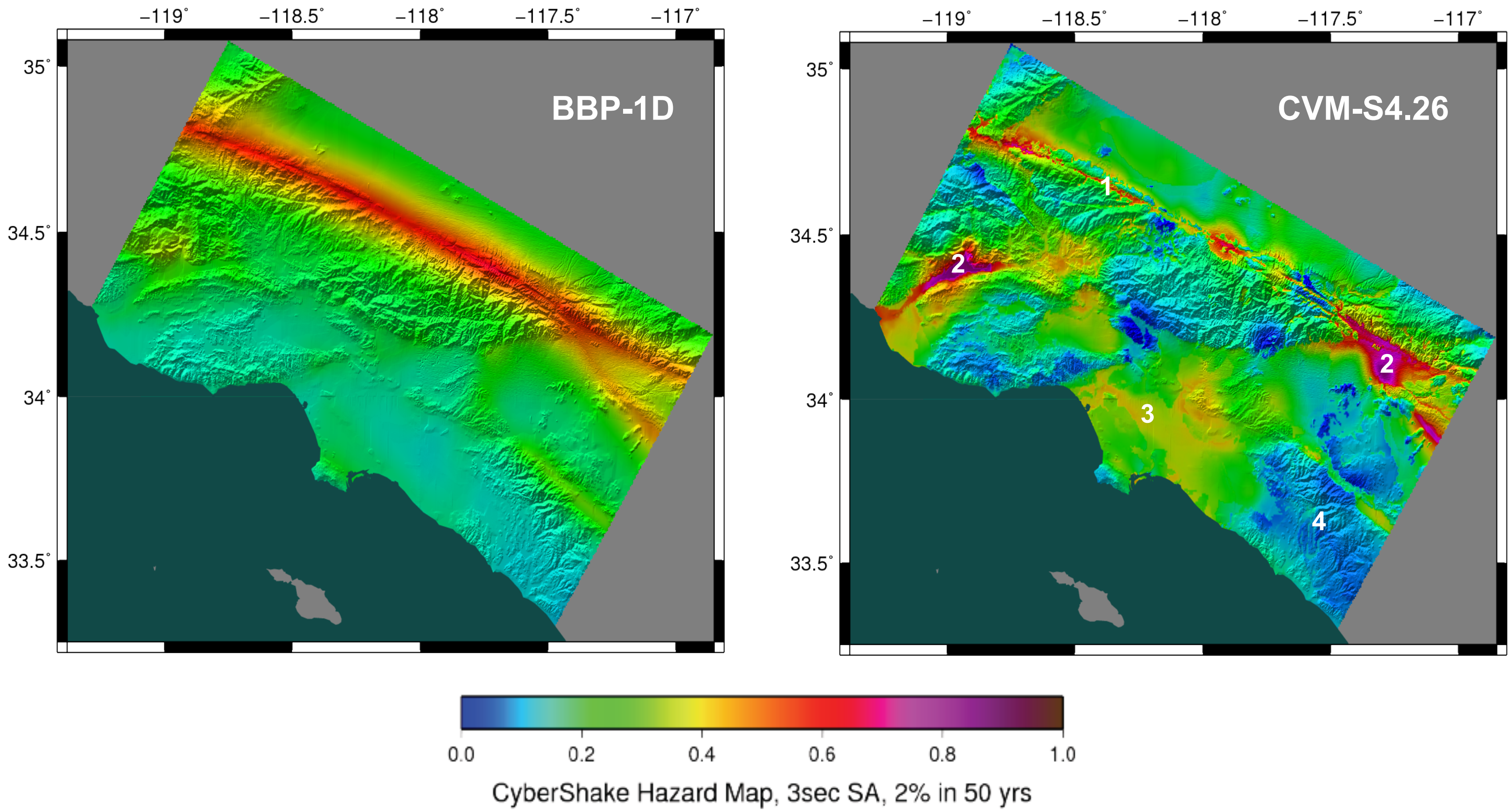
Graves et al. (2011)

CyberShake Model: Physics-Based PSHA

- **Sites:**
  - **283 sites in the greater Los Angeles region**
- **Ruptures:**
  - **All UCERF2 ruptures within 200 km of site (~14,900)**
- **Rupture variations:**
  - **415,000 per site using Graves-Pitarka pseudo-dynamic rupture model**
- **Seismograms:**
  - **235 million per model**

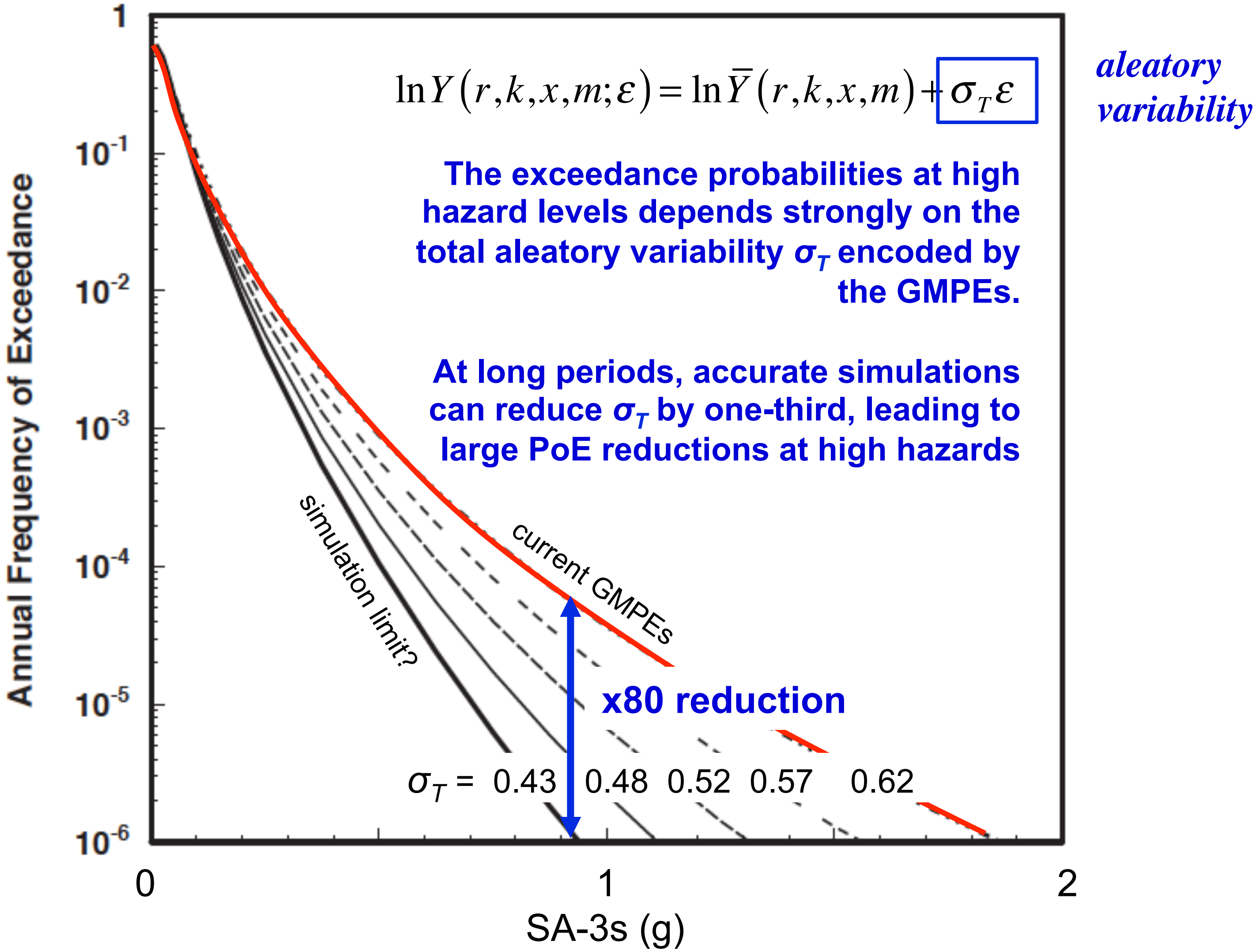


Comparison of 1D and 3D CyberShake Models for the Los Angeles Region

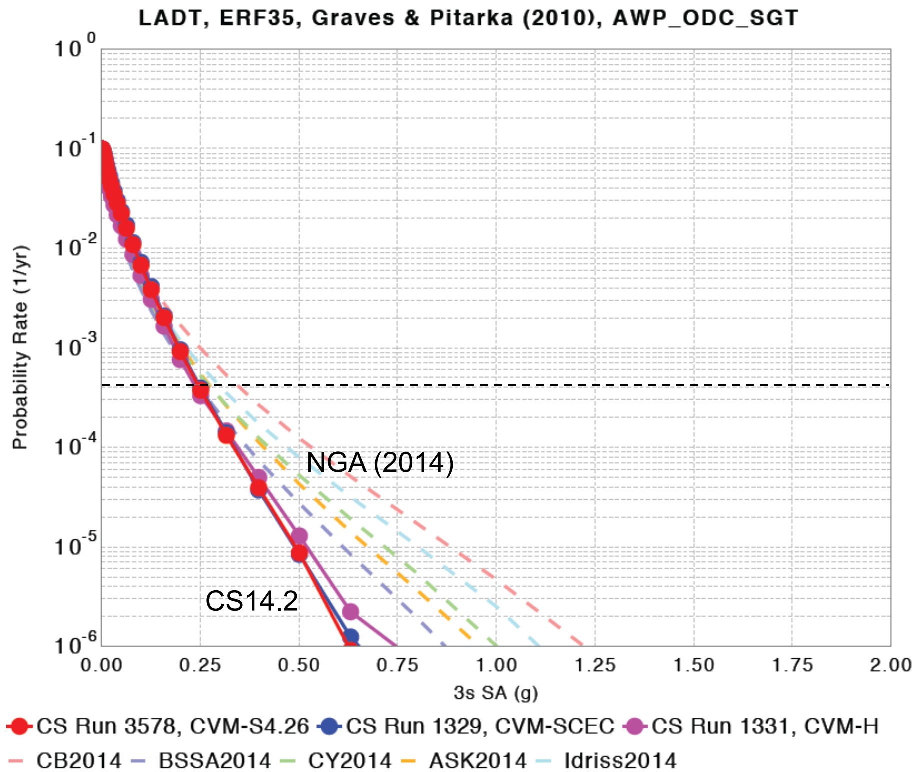


1. lower near-fault intensities due to 3D scattering
2. much higher intensities in near-fault basins
3. higher intensities in the Los Angeles basins
4. lower intensities in hard-rock areas

Importance of Reducing Aleatory Variability

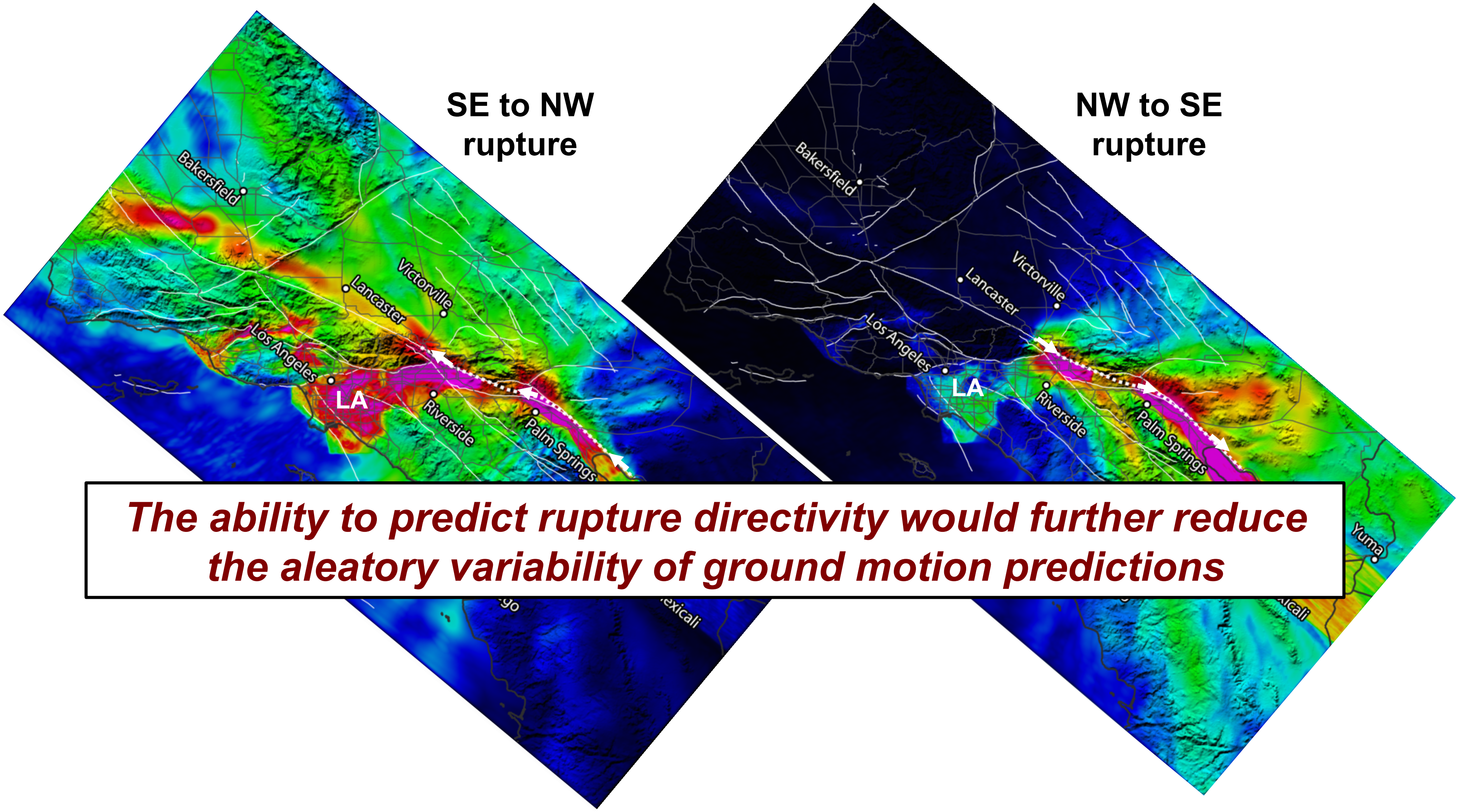


NGA(2014)-CyberShake Hazard Curve Comparisons



Site LADT
(Los Angeles)

Coupling of Directivity and Basin Effects



The ability to predict rupture directivity would further reduce the aleatory variability of ground motion predictions

TeraShake simulations of M7.7 earthquake on Southernmost San Andreas

Scales of Seismic Hazard Change

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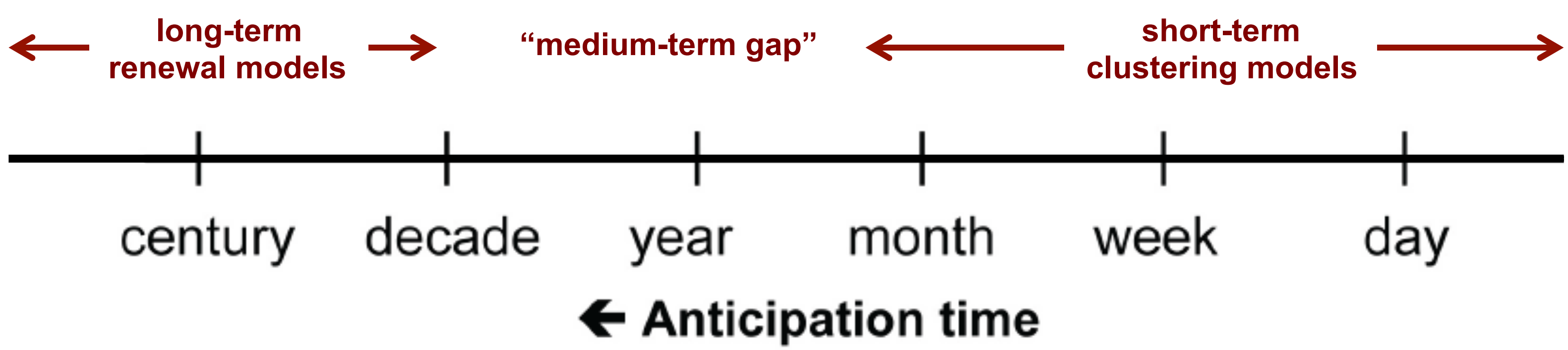
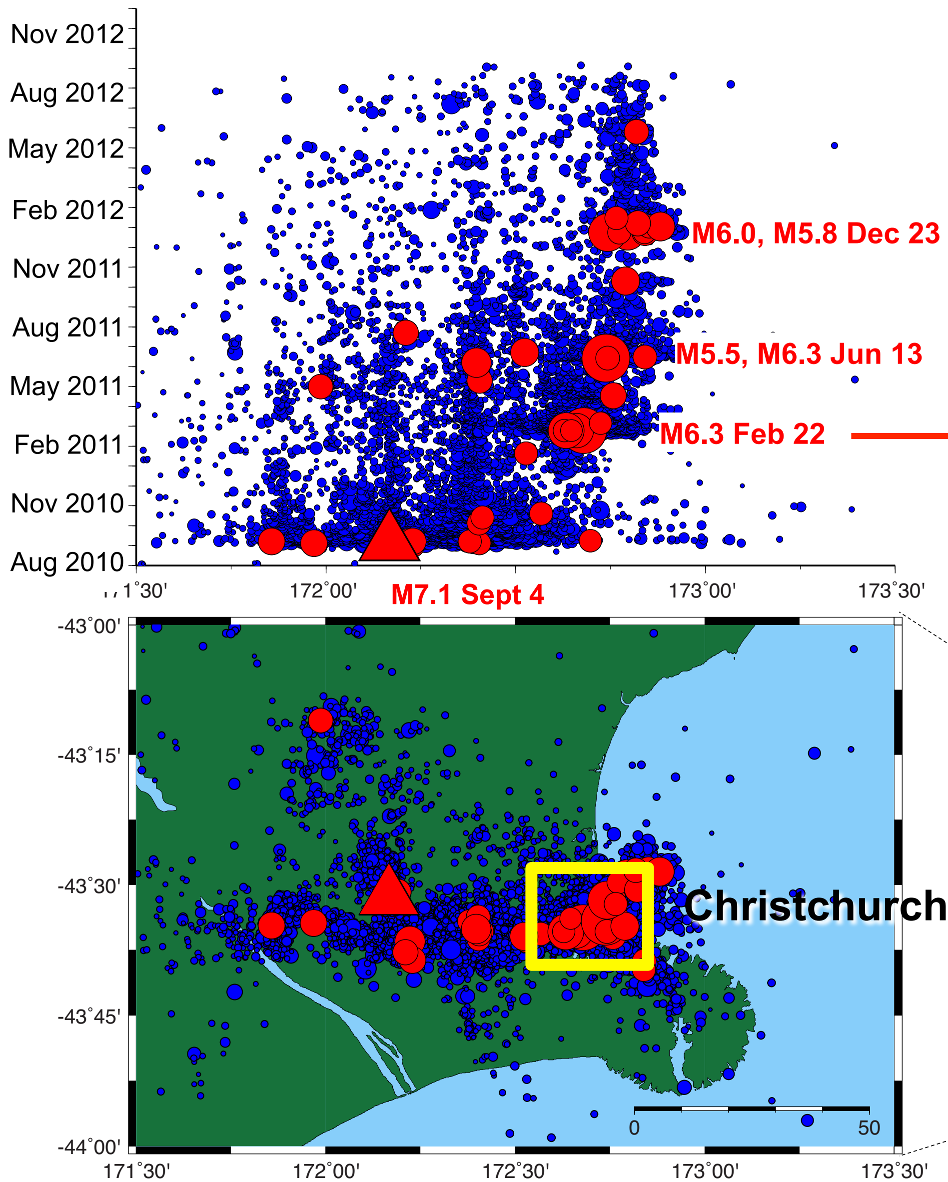


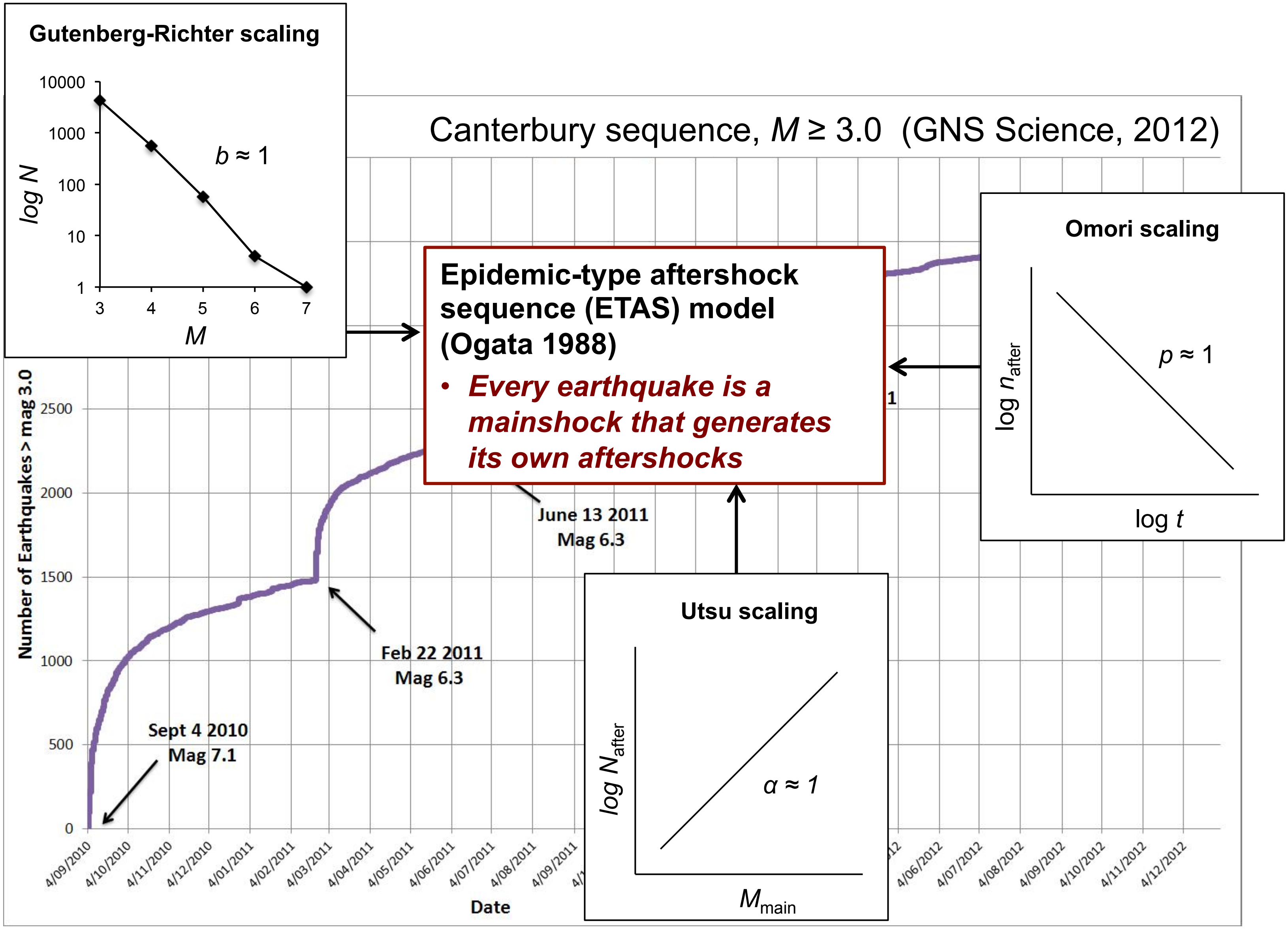
Canterbury Earthquake Sequence



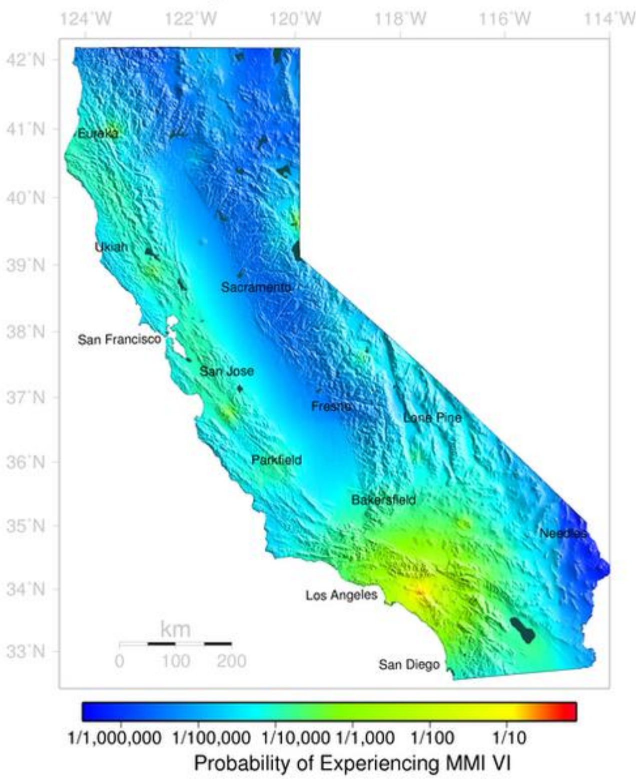
What is the current seismic hazard in Christchurch?

Epicentral dots scaled by magnitude;
M ≥ 5 in red

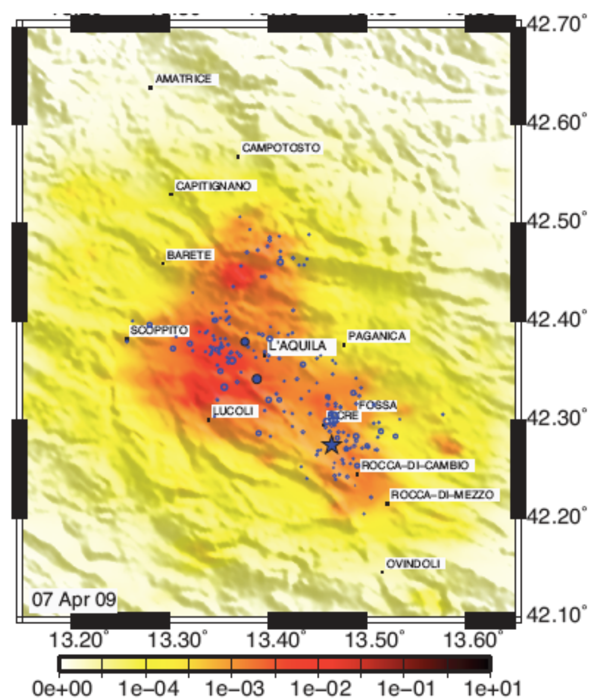
Short-term Forecasting Models



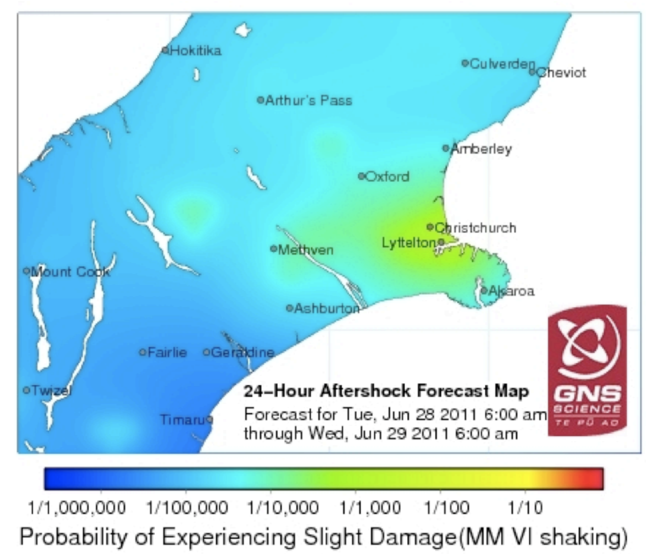
Short-term Forecasting Models



California
29 July 2008
(Gerstenberger et al., 2005)



Italy
7 April 2009
(Marzocchi & Lombardi, 2009)

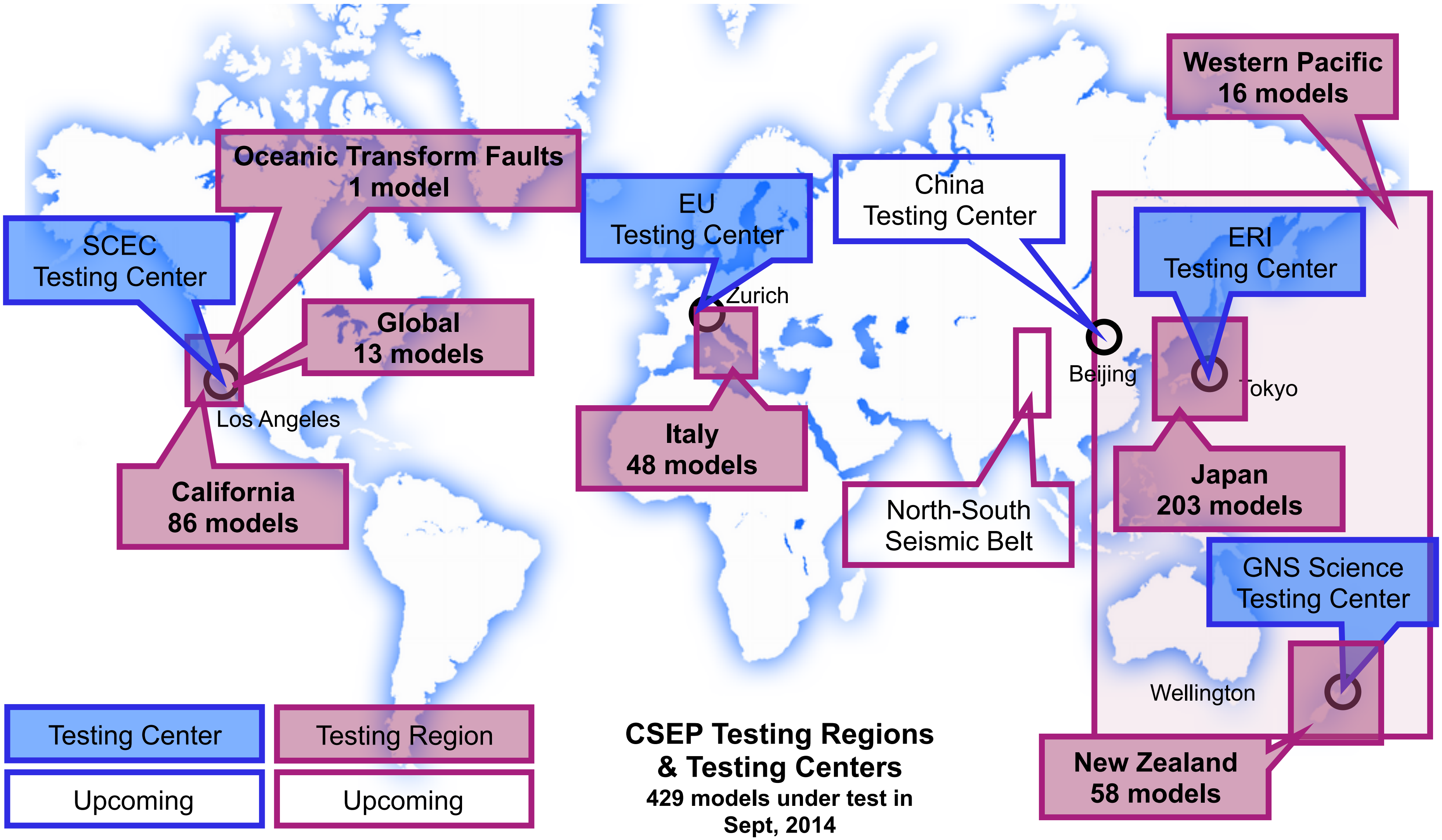


New Zealand
28 June 2011
(Gerstenberger, 2011)

SCEC Southern California Earthquake Center

Collaboratory for the Study of Earthquake Predictability

Infrastructure for automated, blind, prospective testing of forecasting models in a variety of tectonic environments and on a global scale



CSEP Testing in New Zealand

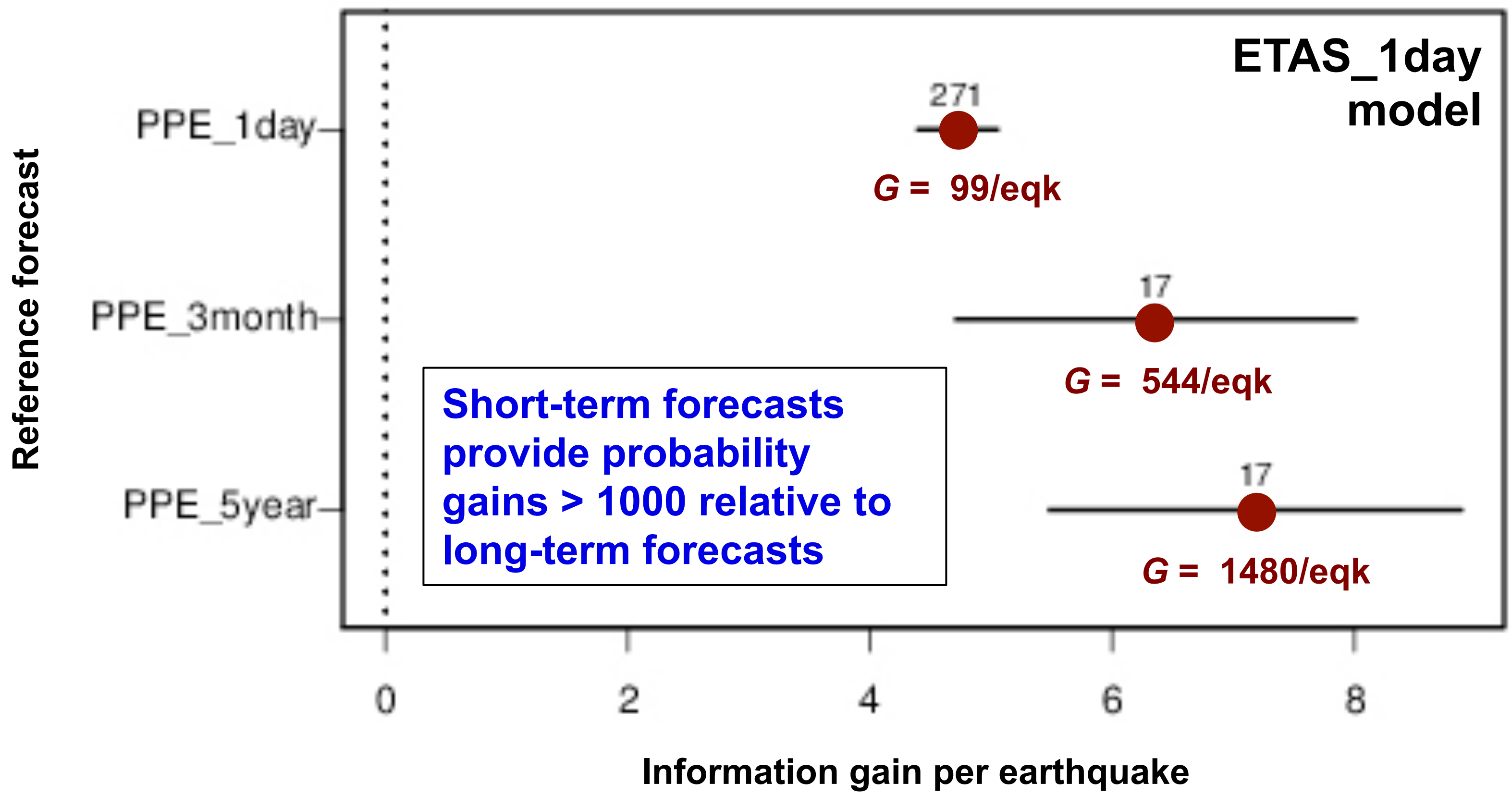
(Gerstenberger & Rhoades, 2012)

Testing region: New Zealand (Canterbury sequence)

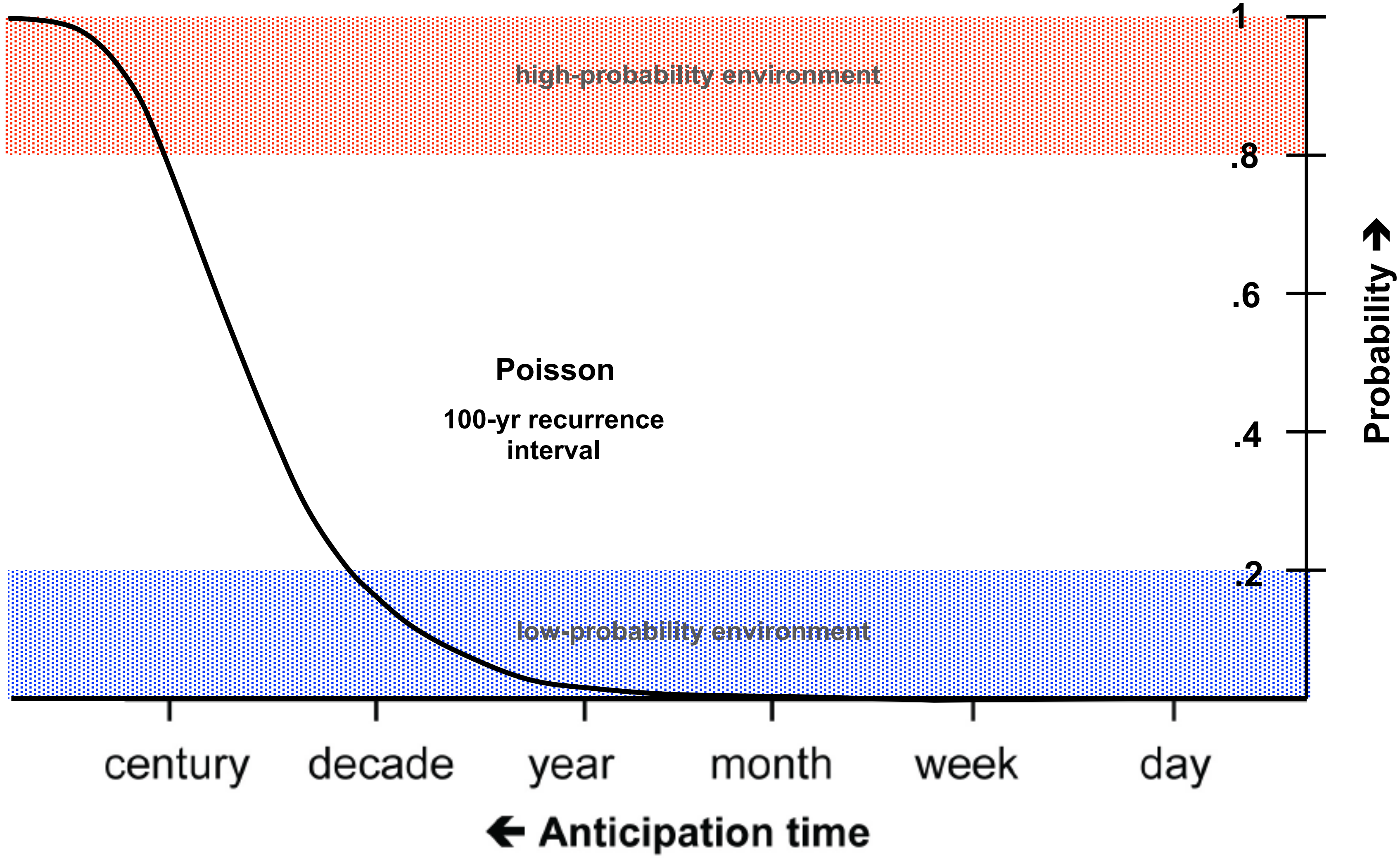
Target events: M ≥ 4 (PPE-1d), M ≥ 5 (PPE-3m, PPE-5y)

Testing period: 4 Sept 2010 - 8 Mar 2011

Testing method: T-test



Scales of Seismic Hazard Change



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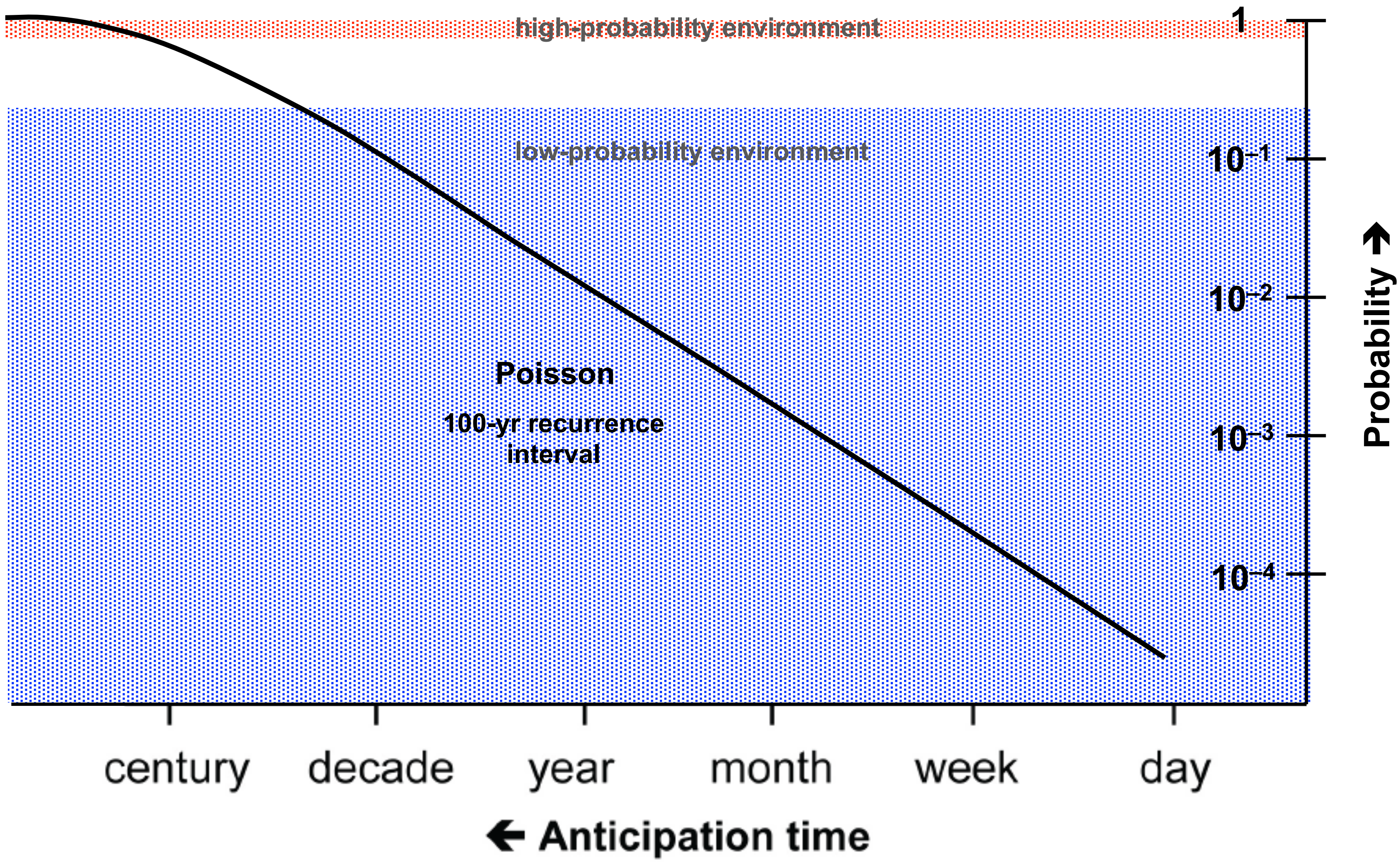

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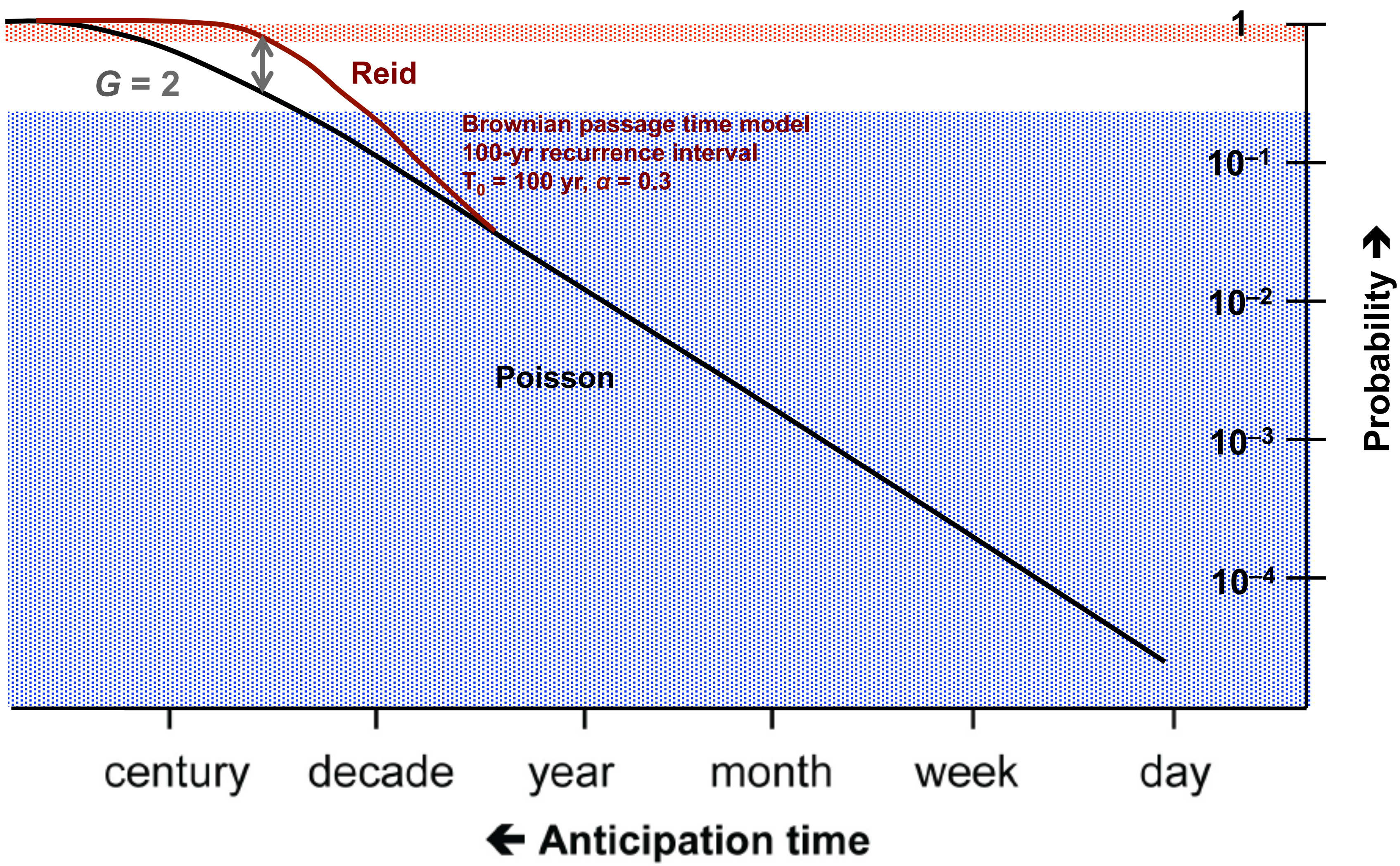

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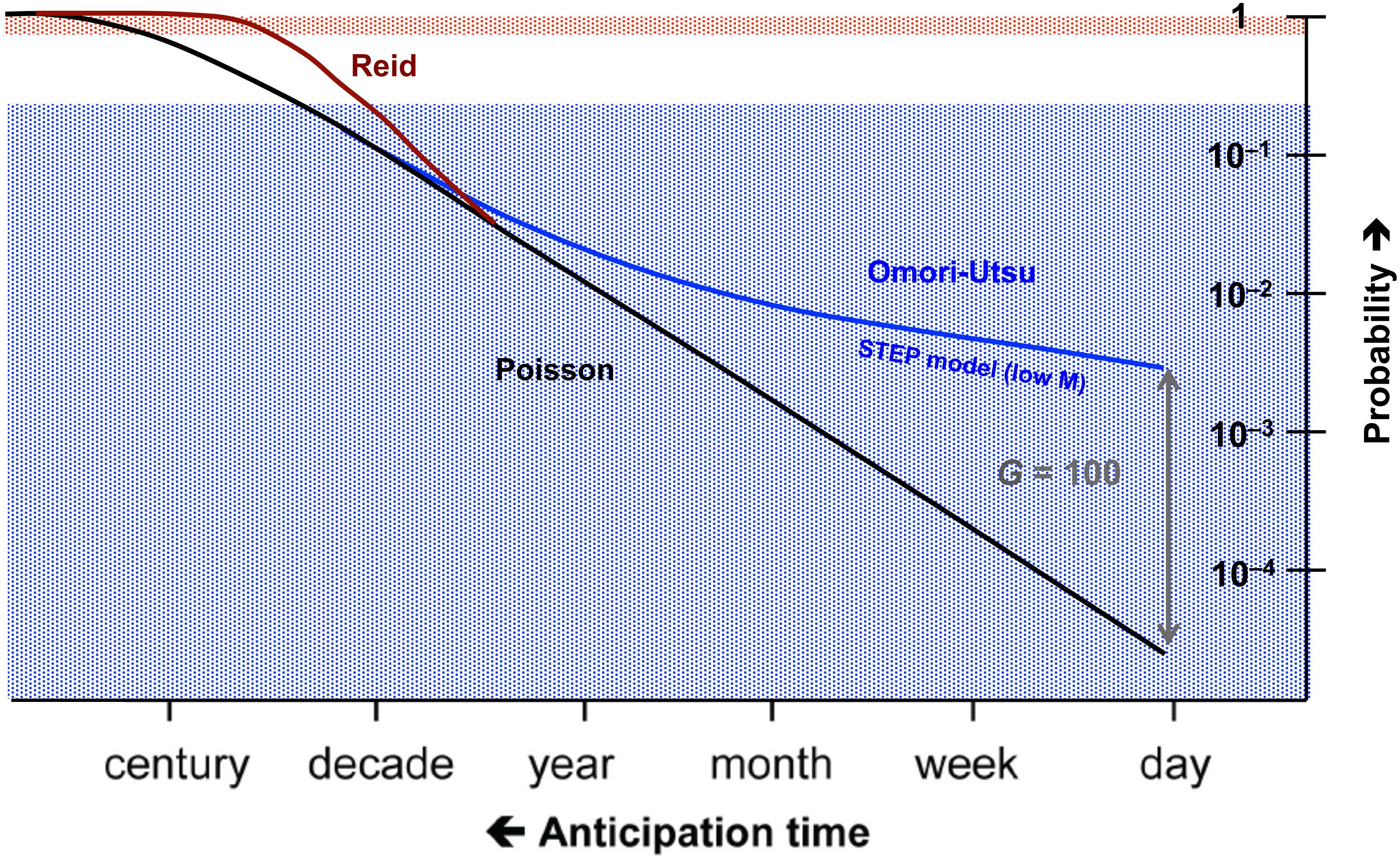

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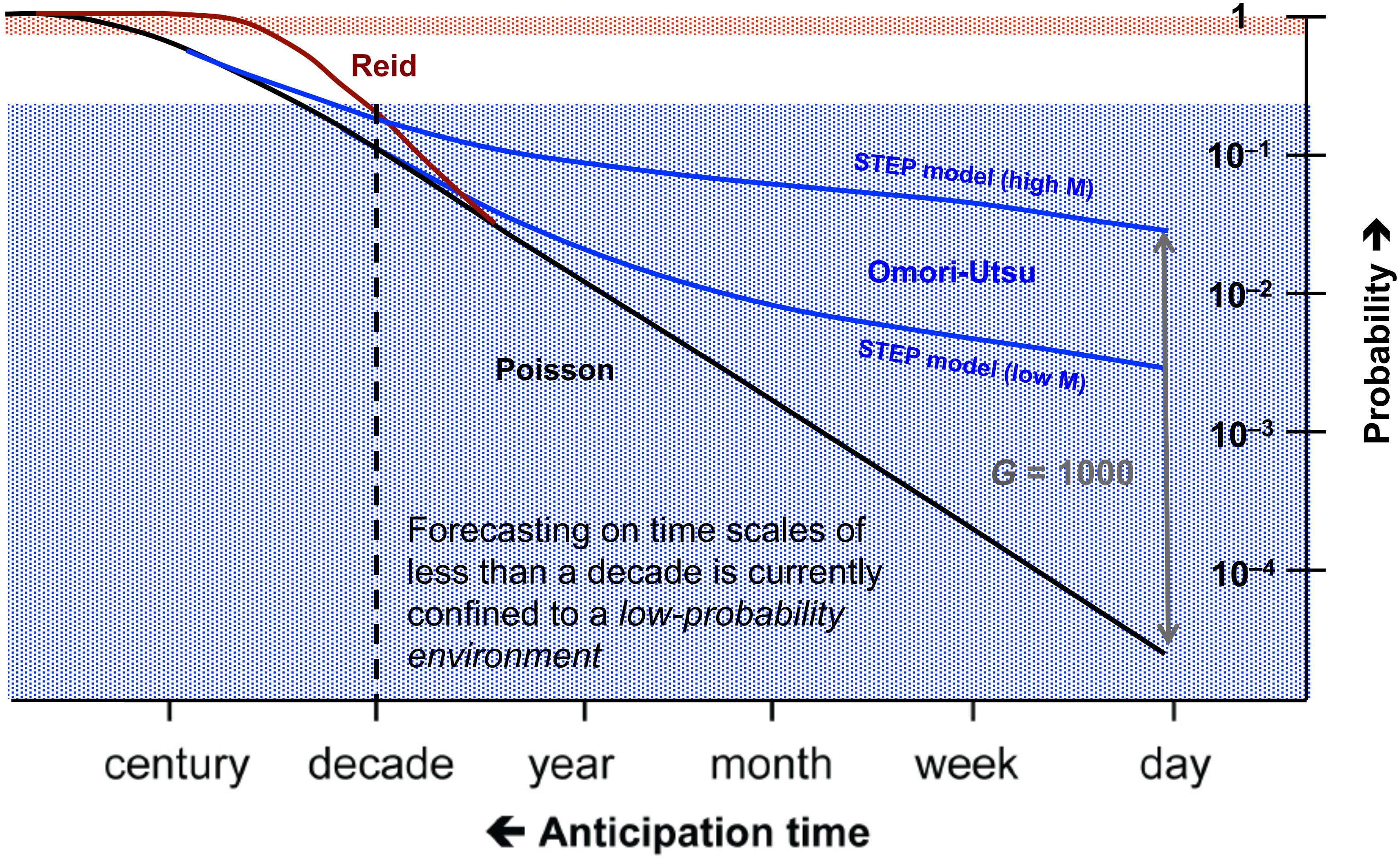


Operational Earthquake Forecasting

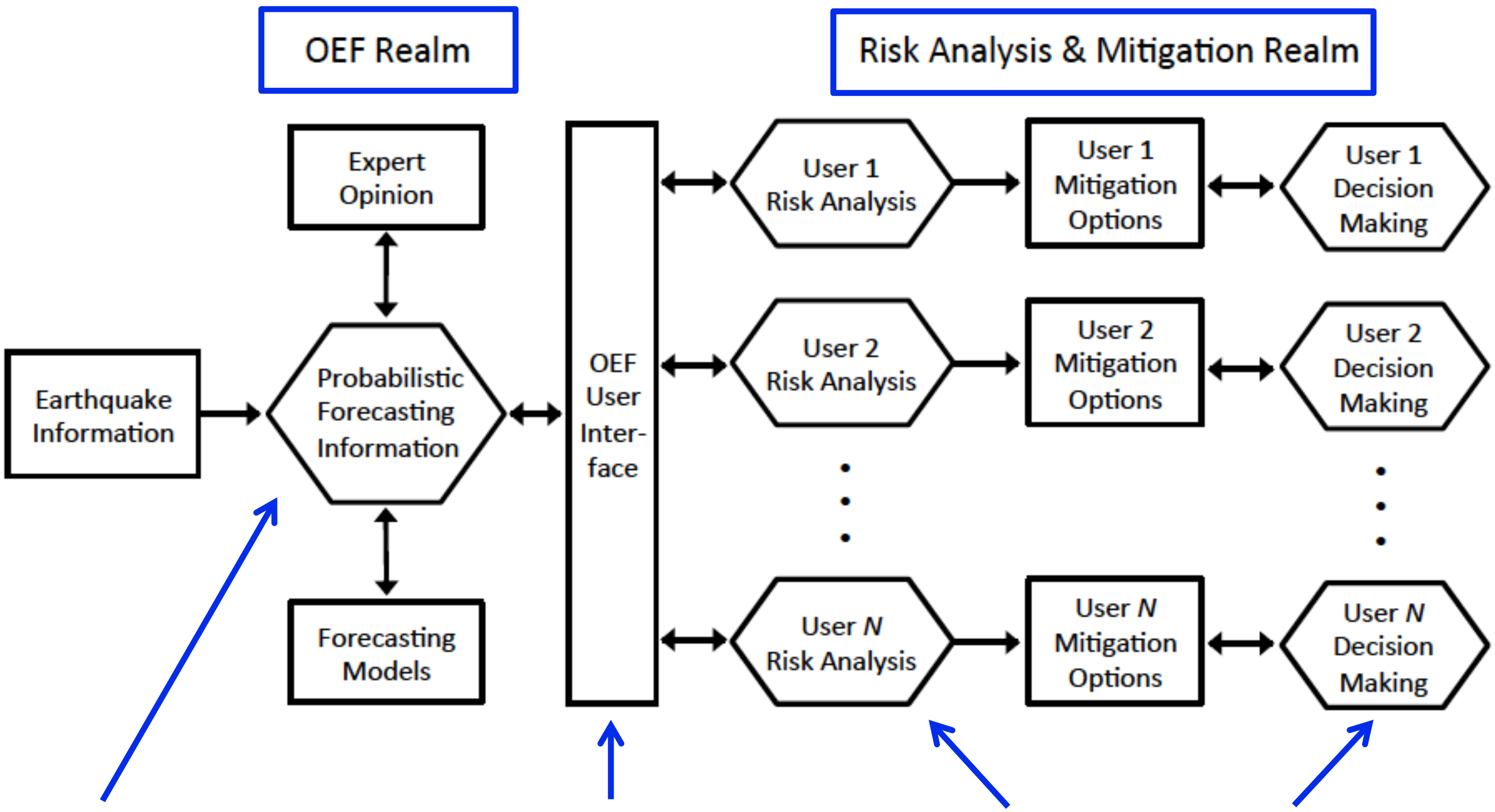
Timely dissemination of authoritative information about the future occurrence of potentially damaging earthquakes to reduce risk and enhance earthquake preparedness in threatened communities

Problems that confront the deployment of OEF systems:

- **While the probability gains of short-term, seismicity-based forecasts can be high (> 1000 relative to long-term forecasts), the probabilities of large earthquakes typically remain low (< 1% per day)**
  - **Preparedness actions appropriate in such high-gain, low-probability situations have not been systematically developed**
- **Standardization of OEF methods and protocols is in a nascent stage**
  - **Incremental benefits of OEF for civil protection (e.g., relative to long-term seismic hazard analysis) have not been convincingly demonstrated**
- **Under these circumstances, the responsible governmental agencies have been cautious in deploying OEF capabilities**
  - **Progress has been made in New Zealand (on-going Canterbury sequence) and Italy (in response to the 2009 L'Aquila earthquake)**

Operational Earthquake Forecasting System

- *Transparency Principle*: **Short-term forecasting information must be delivered to the public quickly, transparently, authoritatively, and on a continuing basis**
- *Separation Principle*: **The OEF realm of hazard assessment should be kept distinct from the risk-analysis & mitigation realm of OEF users**



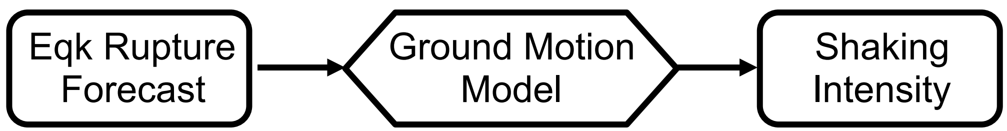
Provisioning of probabilistic forecasts and their epistemic uncertainties

Conditioning of forecasting information for a multiplicity of users

Allowance for many types of users, each with their own risk framework and thresholds for action

Coupling CyberShake and UCERF3 to Forecast Time-Dependent Ground Motion Probabilities

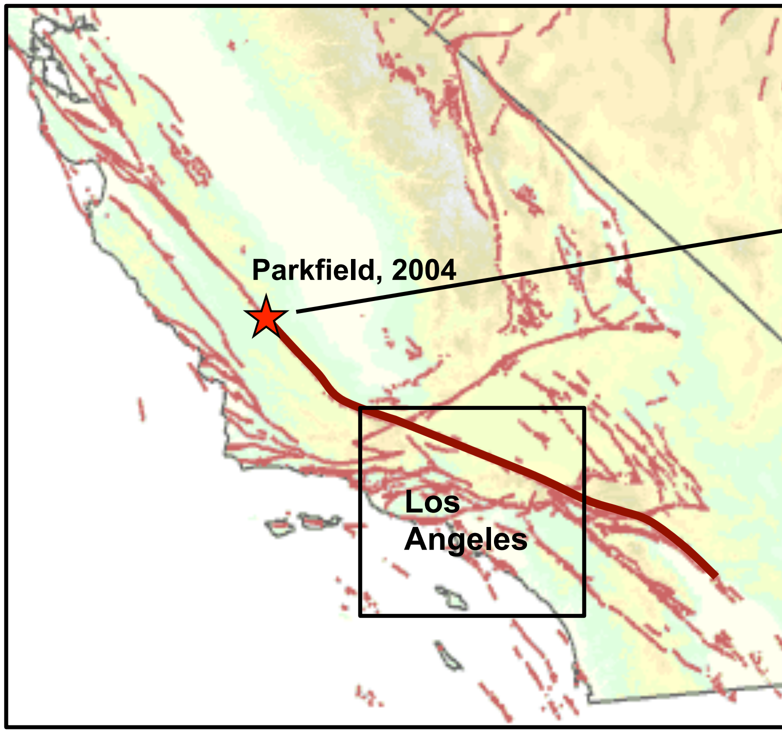
- **Pre-computed CyberShake ground motion models are easily coupled to short-term forecasting models, such UCERF3-ETAS**
  - **Output is a time-dependent seismic hazard estimate**

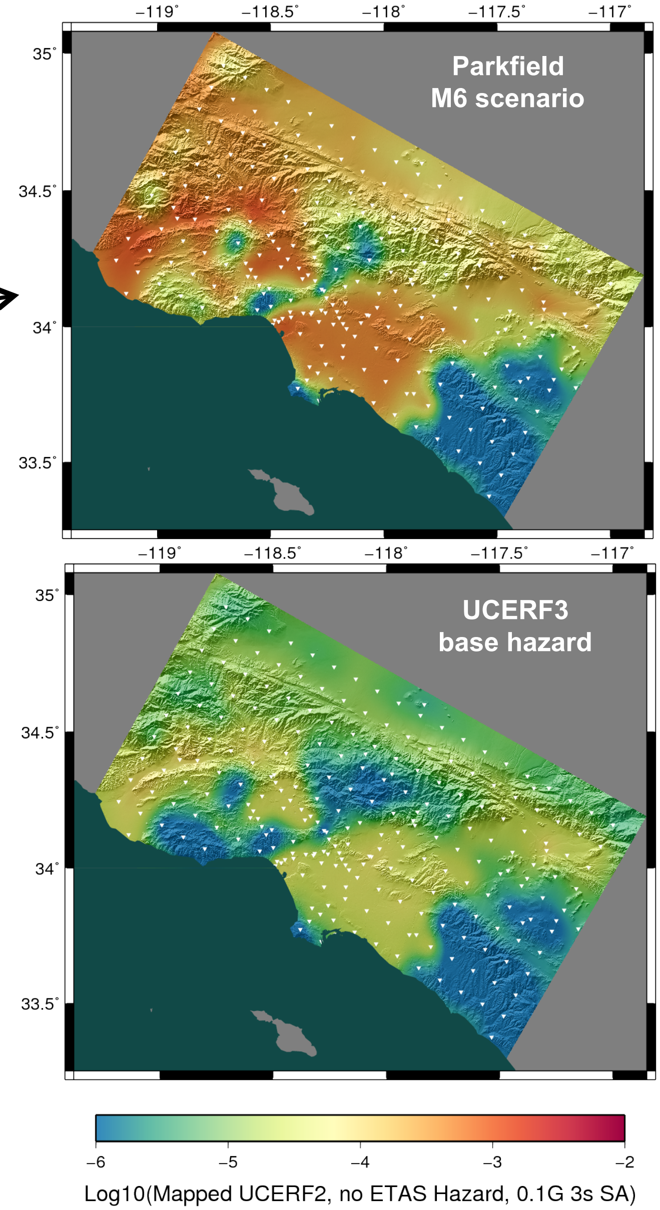


$P(S_k, T)$ $P(Y_n / S_k)$ $P(Y_k, T)$ **T = forecast time**

- **Short-term forecasting localizes epicenter probabilities**
  - **Coupled model achieves significant gains in ground motion probabilities through the forecasting of source directivity and directivity-basin coupling**

UCERF3-CyberShake Aftershock Forecast for M6 Scenarios





- **UCERF3-CyberShake Aftershock Forecasts for M6 Scenarios**
  - **Based on average of 100,000 UCERF3 simulations of aftershock sequences**
  - **UCERF3 supra-seismogenic fault ruptures mapped onto UCERF2 ruptures in the CyberShake 14.2b model**

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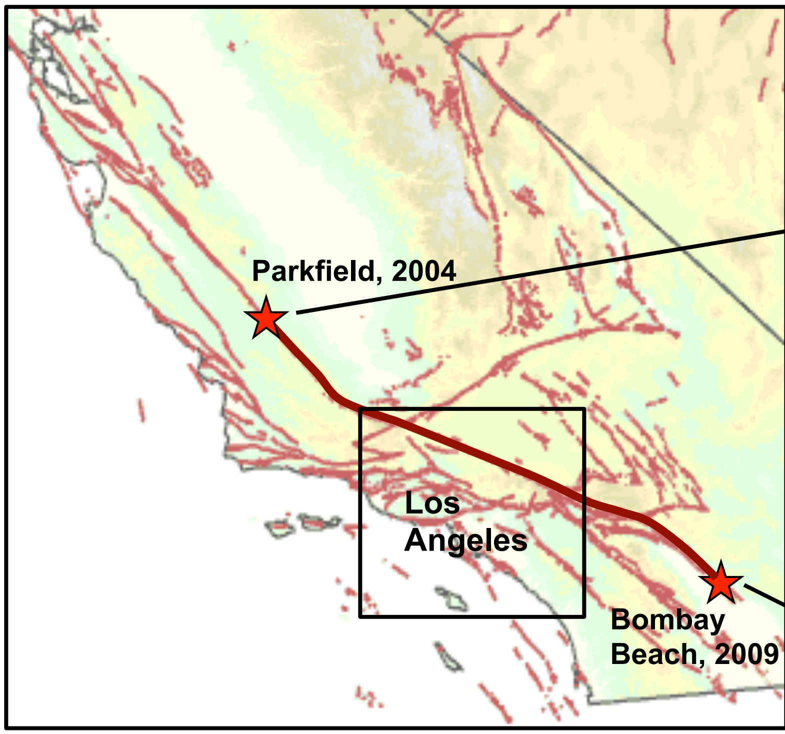

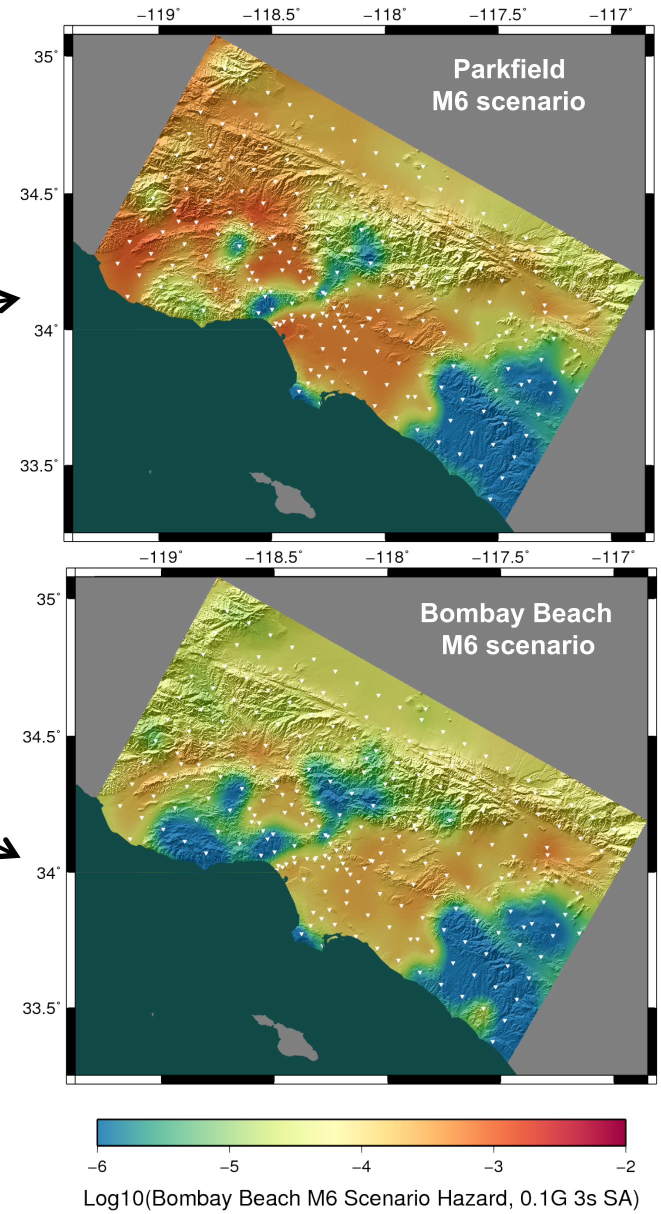

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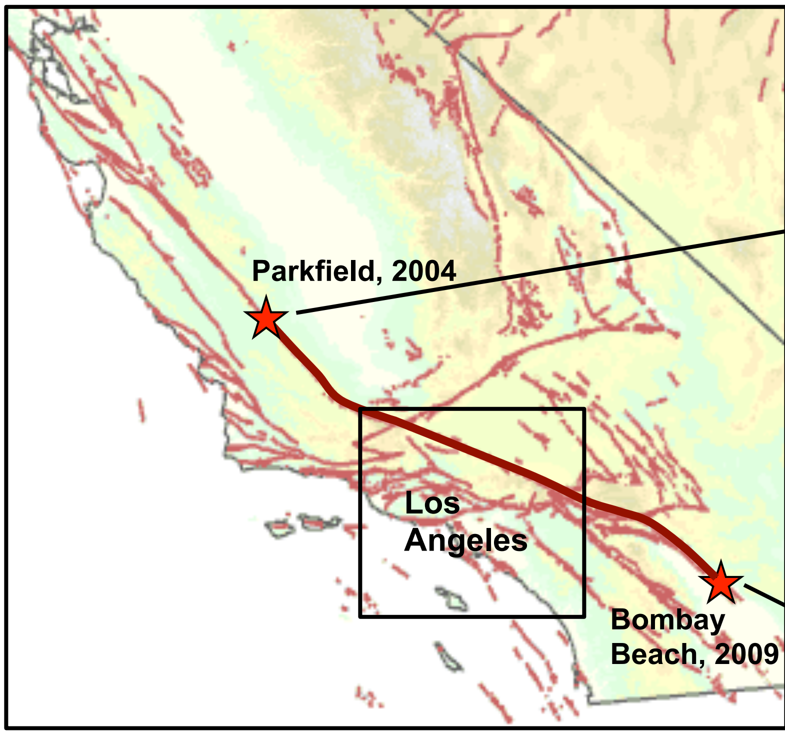
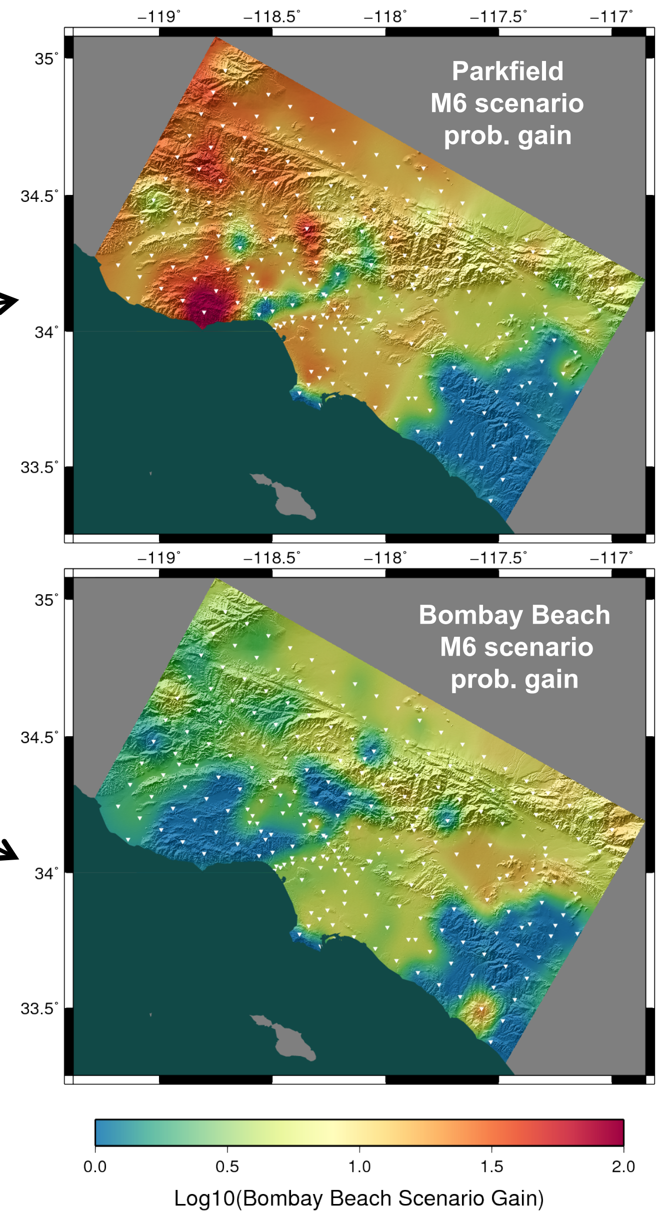
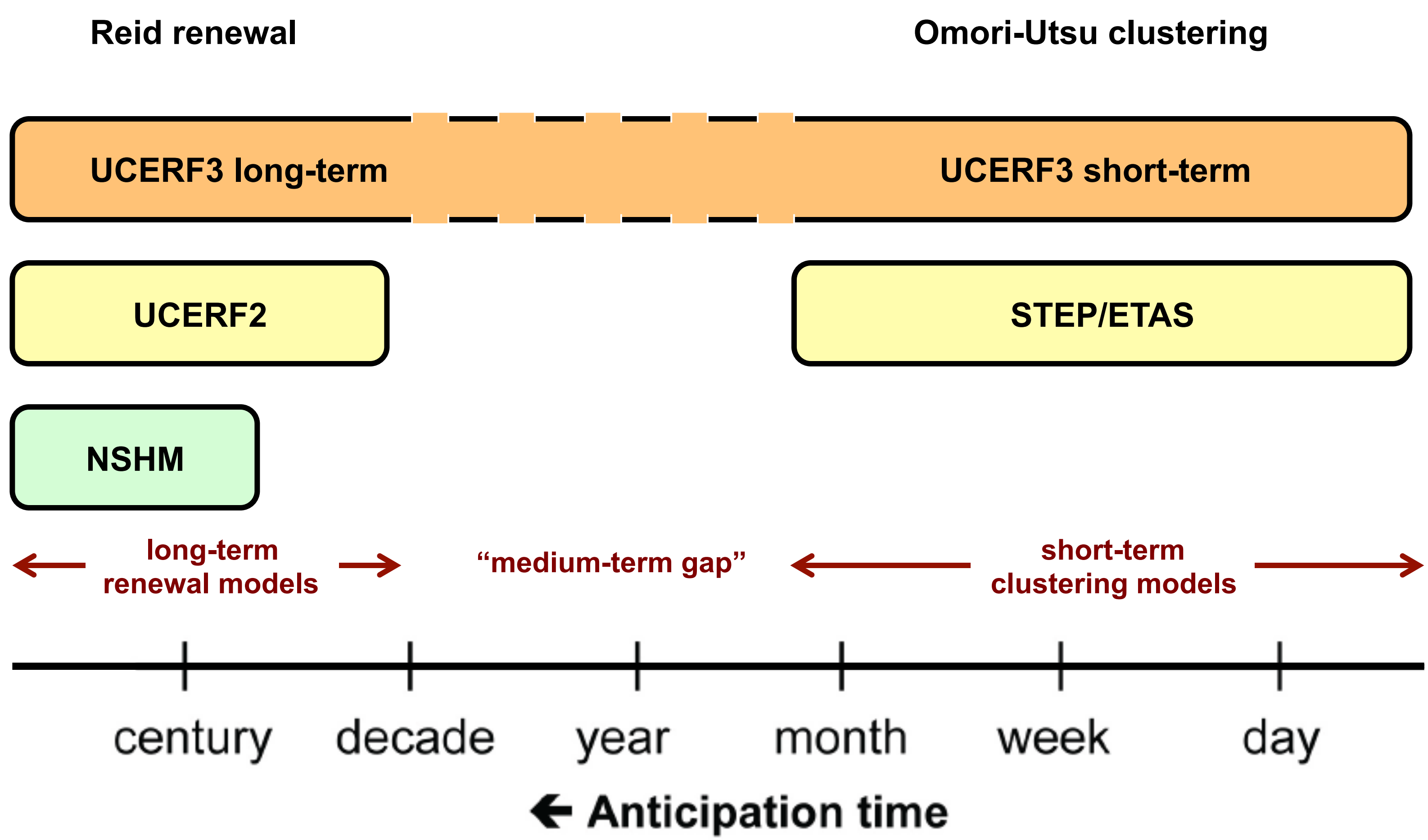
UCERF3-CyberShake Aftershock Forecast for M6 Scenarios



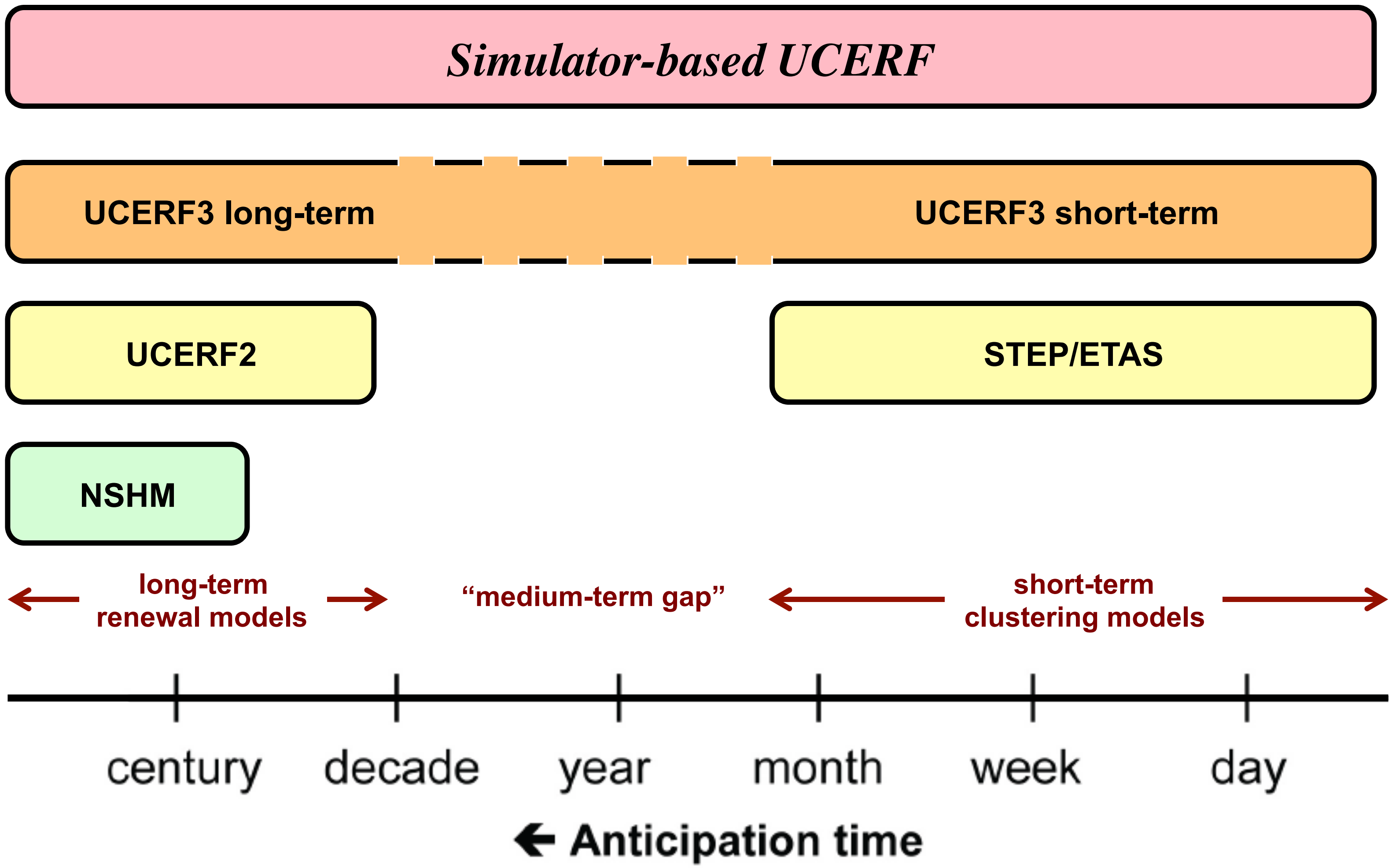


- **UCERF3-CyberShake Aftershock Forecasts for M6 Scenarios**
  - **Based on average of 100,000 UCERF3 simulations of aftershock sequences**
  - **UCERF3 supra-seismogenic fault ruptures mapped onto UCERF2 ruptures in the CyberShake 14.2b model**

California Earthquake Forecasting Models



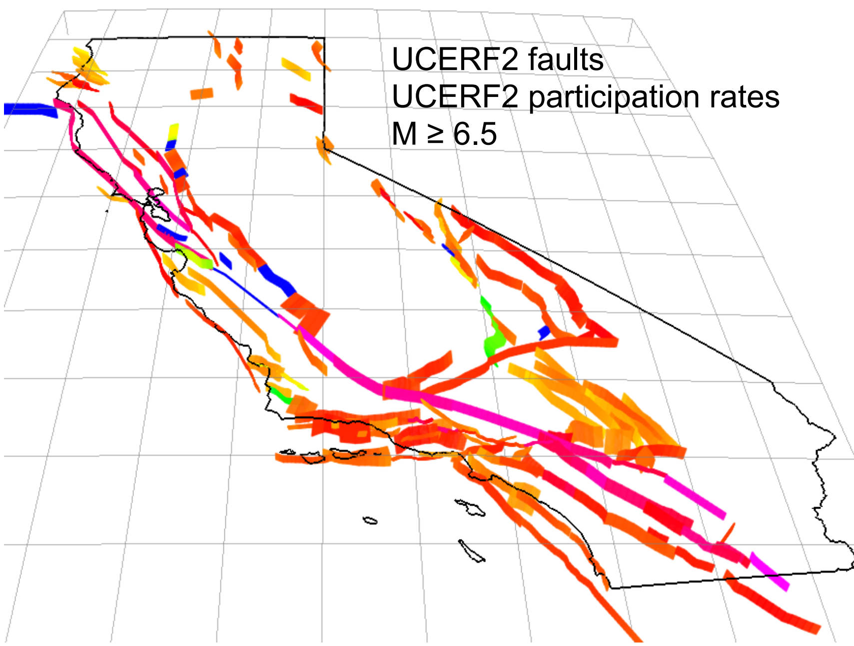
California Earthquake Forecasting Models

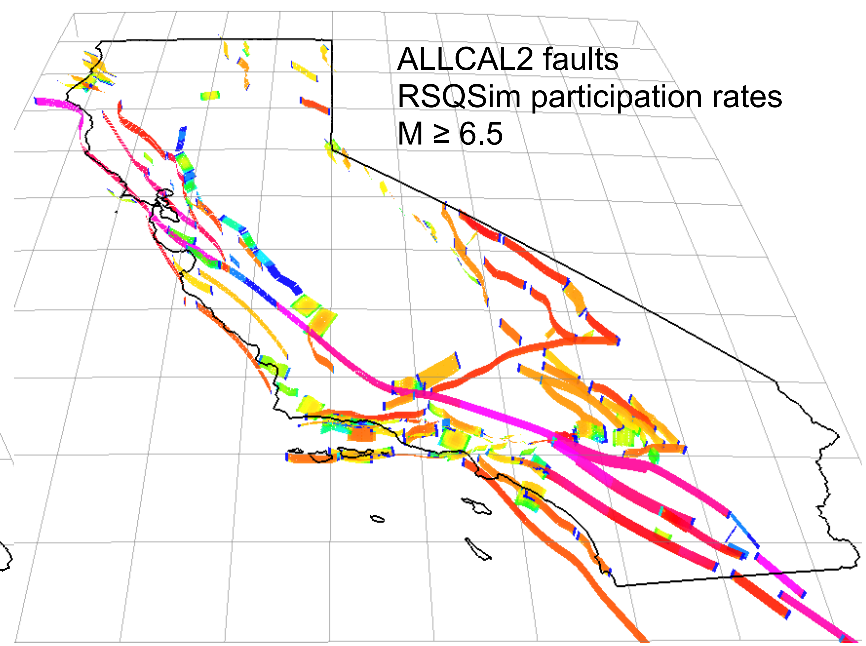


RSQSim Earthquake Simulator

(Dieterich, 1995; Dieterich & Richards-Dinger, 2010; Richards-Dinger & Dieterich, 2012)

- **Tectonic loading of faults by backslip approximation**
- **Rupture nucleation by rate- and state-dependent friction**
- **Radiation damping and dynamic overshoot**
- **Slip-mediated stress transfer in homogeneous elastic halfspace**
- **Very efficient 3-state computational algorithm**

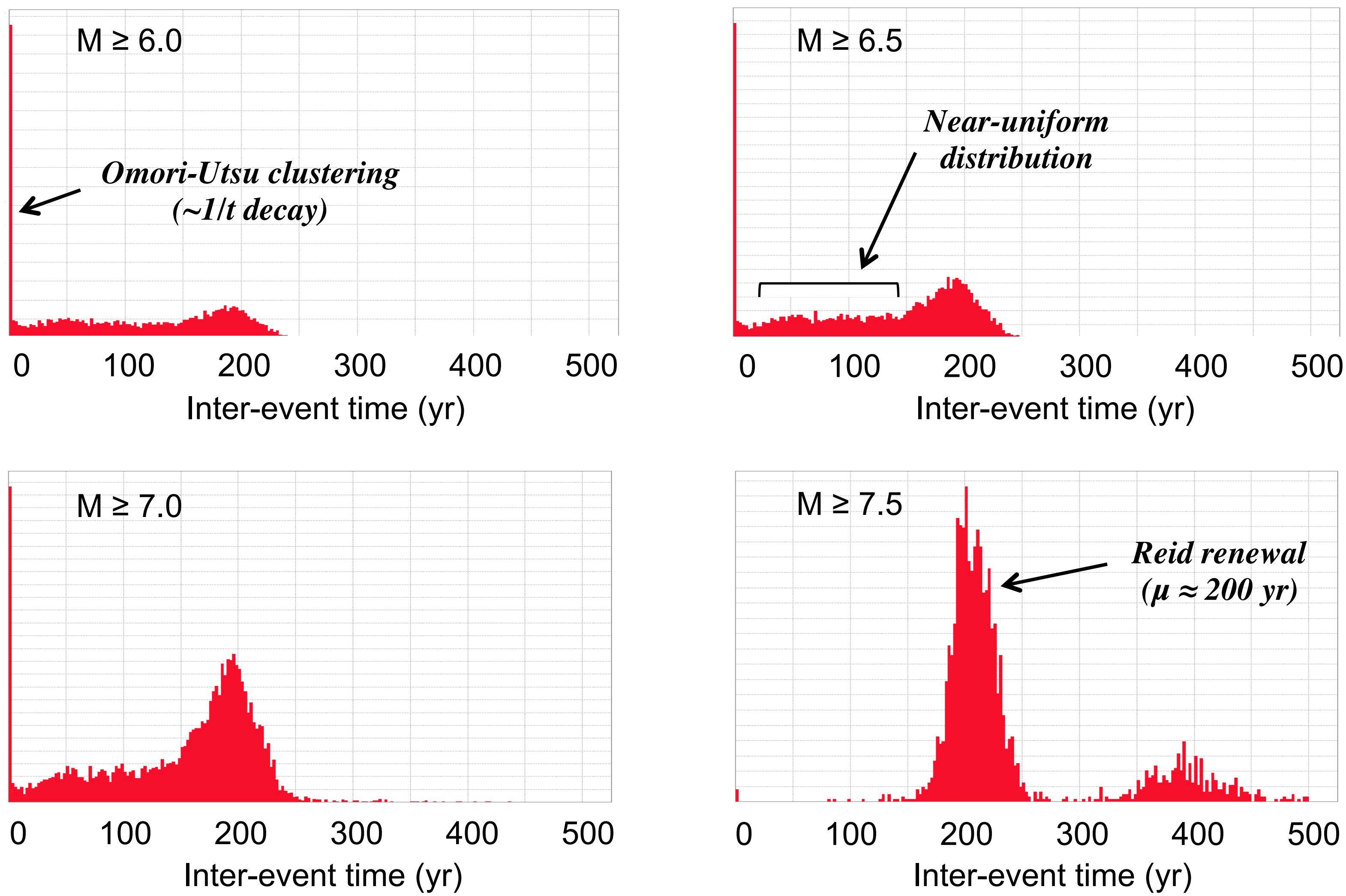




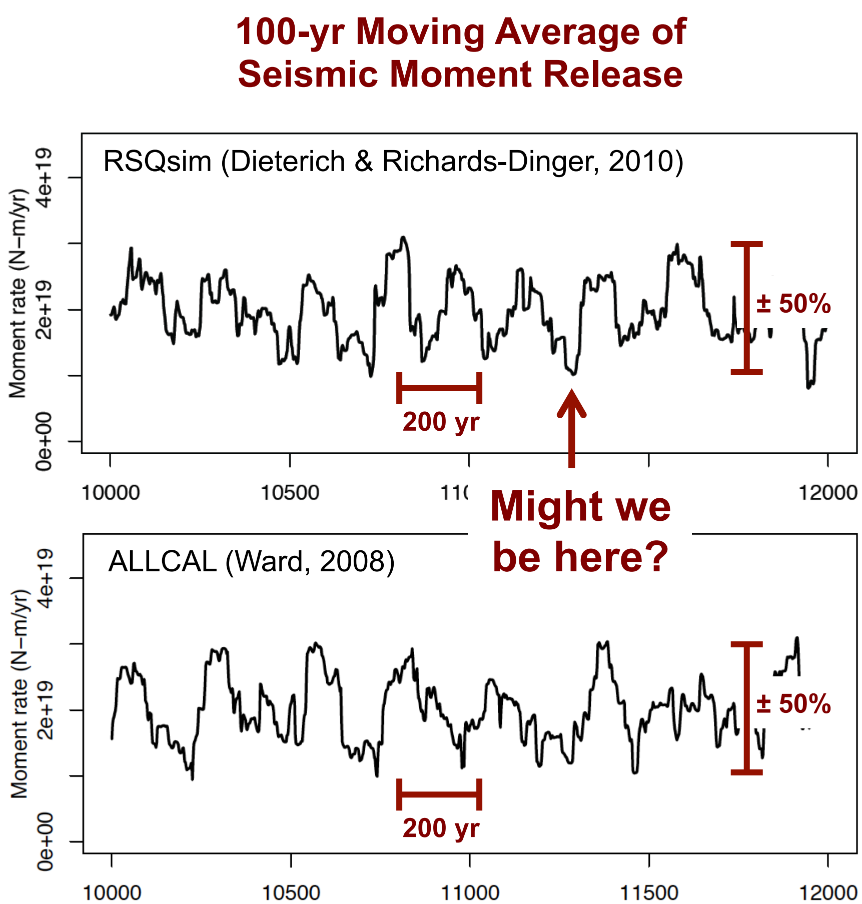
RSQSim Earthquake Simulator

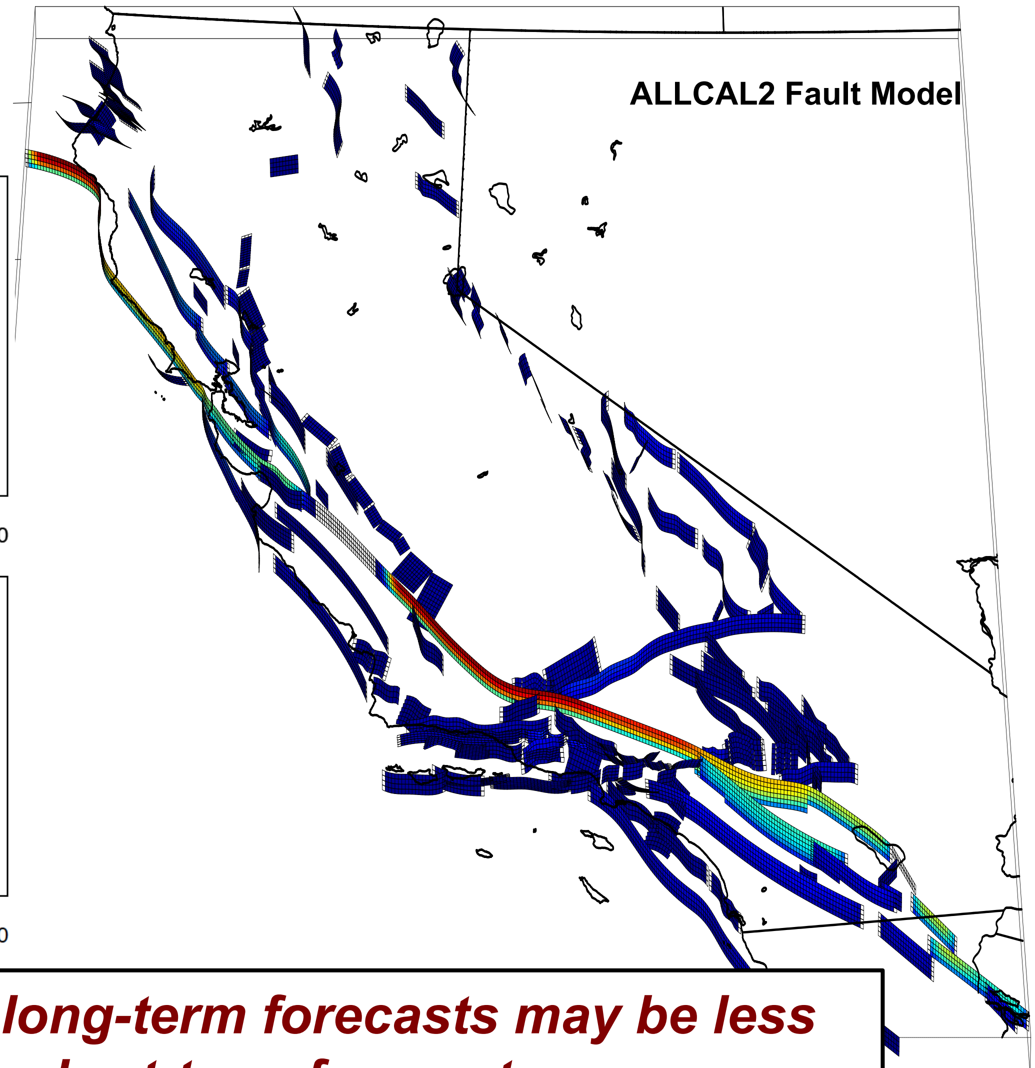
(Dieterich, 1995; Dieterich & Richards-Dinger, 2010; Richards-Dinger & Dieterich, 2012)

Magnitude dependence of inter-event times on the Carrizo-Cholame sections of the San Andreas fault from a million-year catalog



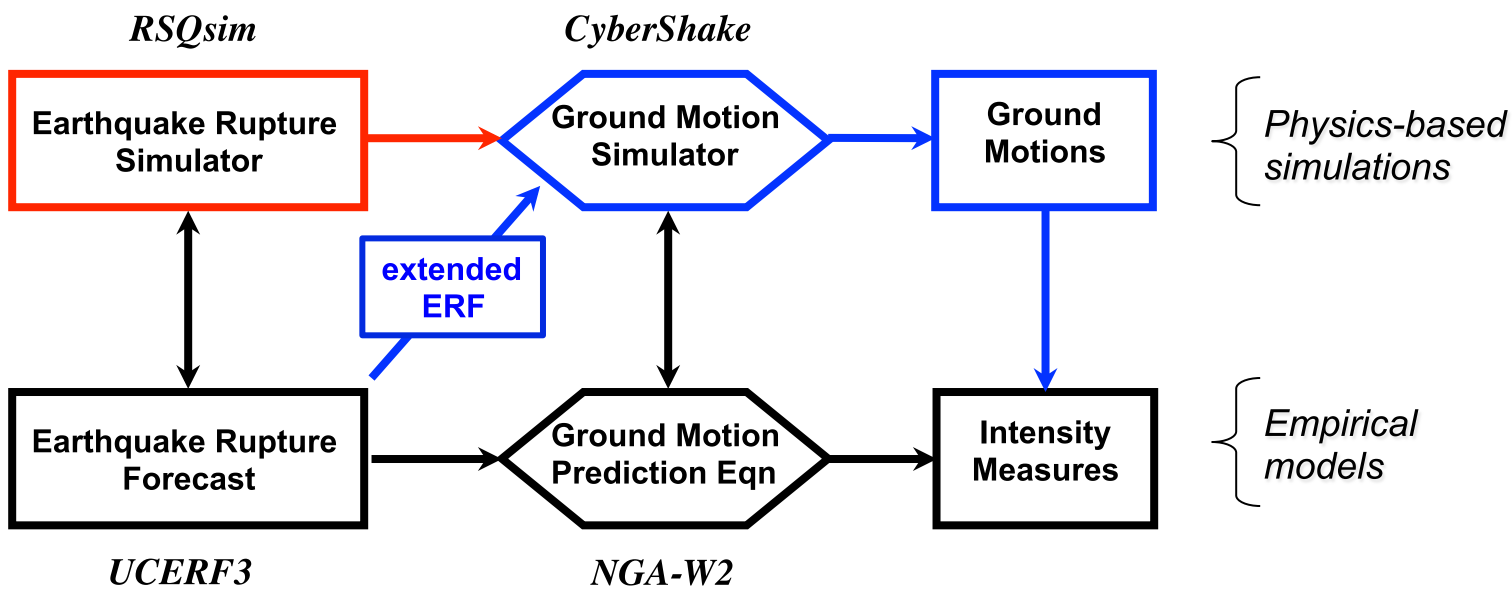
Earthquake Supercycles in Rupture Simulators





Owing to supercycles, our long-term forecasts may be less reliable than our short-term forecasts

Development of Physics-Based Earthquake Forecasting



Conclusions

- **Progress is being made in solving the "fundamental problem of earthquake prediction"**
  - **Brick-by-brick using the probabilistic, rather than deterministic, approach**
- **Current methods can provide useful information for operational earthquake forecasting across a range of temporal scales**
  - **Statistical models of earthquake interactions can capture many of the short-term temporal and spatial features of natural seismicity**
- **Much of the aleatory variability in the conditional forecasting ground motions is due to 3D crustal structure**
  - **Accurate earthquake simulations could reduce the residual variance of the ground motion predictions by a factor of ~2**
- **Physics-based forecasting methods are replacing empirical methods**
  - **A key issue for long-term forecasting in California is the degree of rupture synchronization within the San Andreas fault system**

Thank you!