SCEC Seismic Hazard Analysis Platforms

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Many collaborators, including Ned Field, Bruce Shaw,
Christine Goulet, Tom Jordan, Scott Callaghan, Phil Maechling

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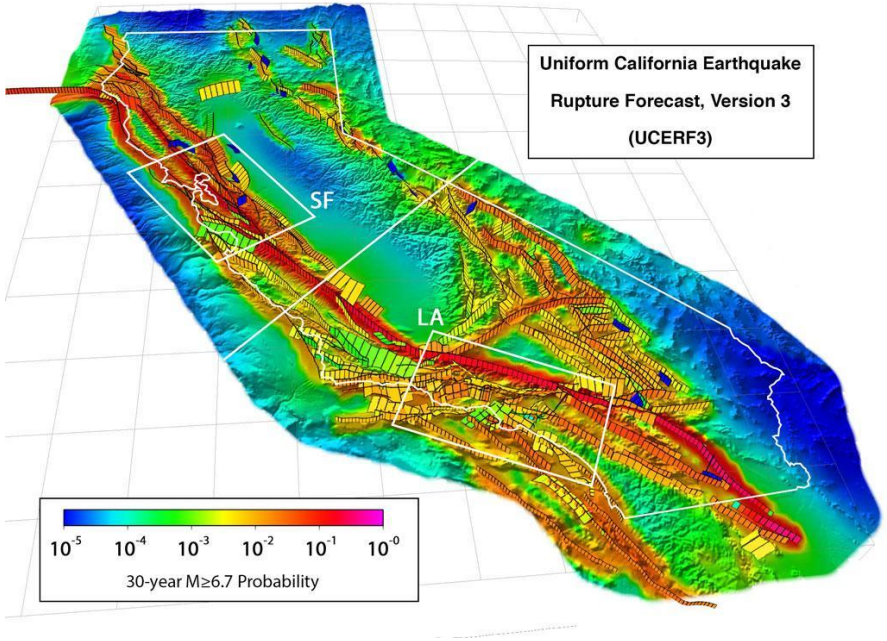
PSHA Components

- Probabilistic Seismic Hazard Analysis (PSHA) involves two main model components:

1) Earthquake ***Rupture*** Forecast

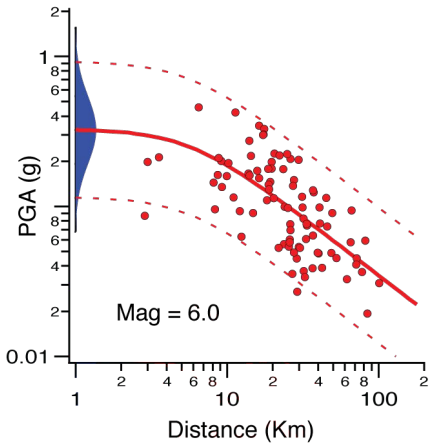
Gives the probability of all possible earthquake ruptures throughout the region and over a specified time span



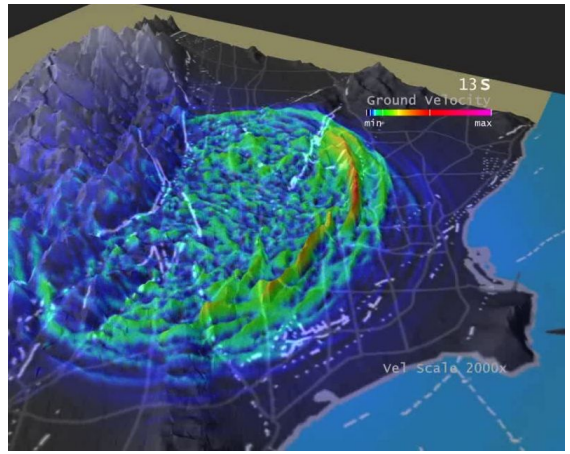
2) Earthquake ***Shaking*** model

For a given earthquake rupture, this gives the probability that an intensity-measure type will exceed some level of concern

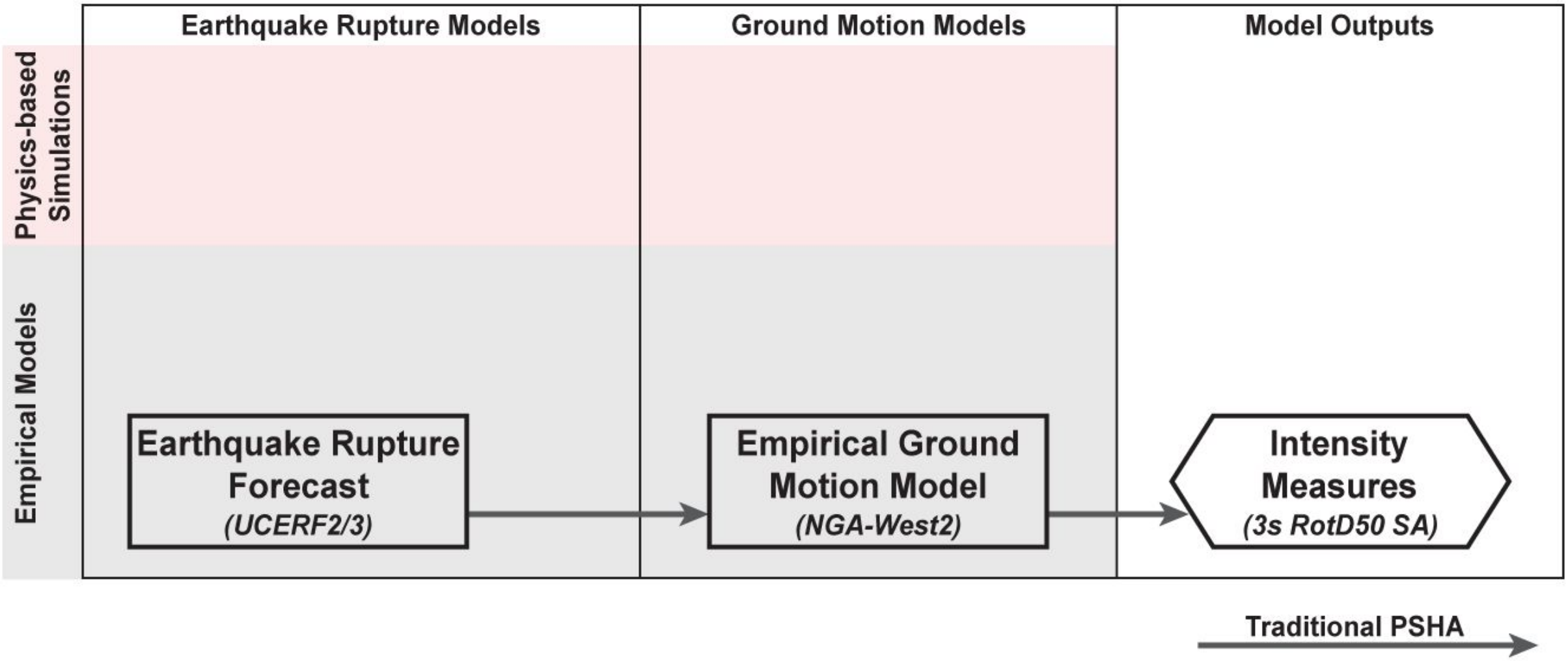
Empirical "Ground Motion Models"



Physics-based "Waveform Modeling"



PSHA Pathways



(Milner et al., 2021, *BSSA*)

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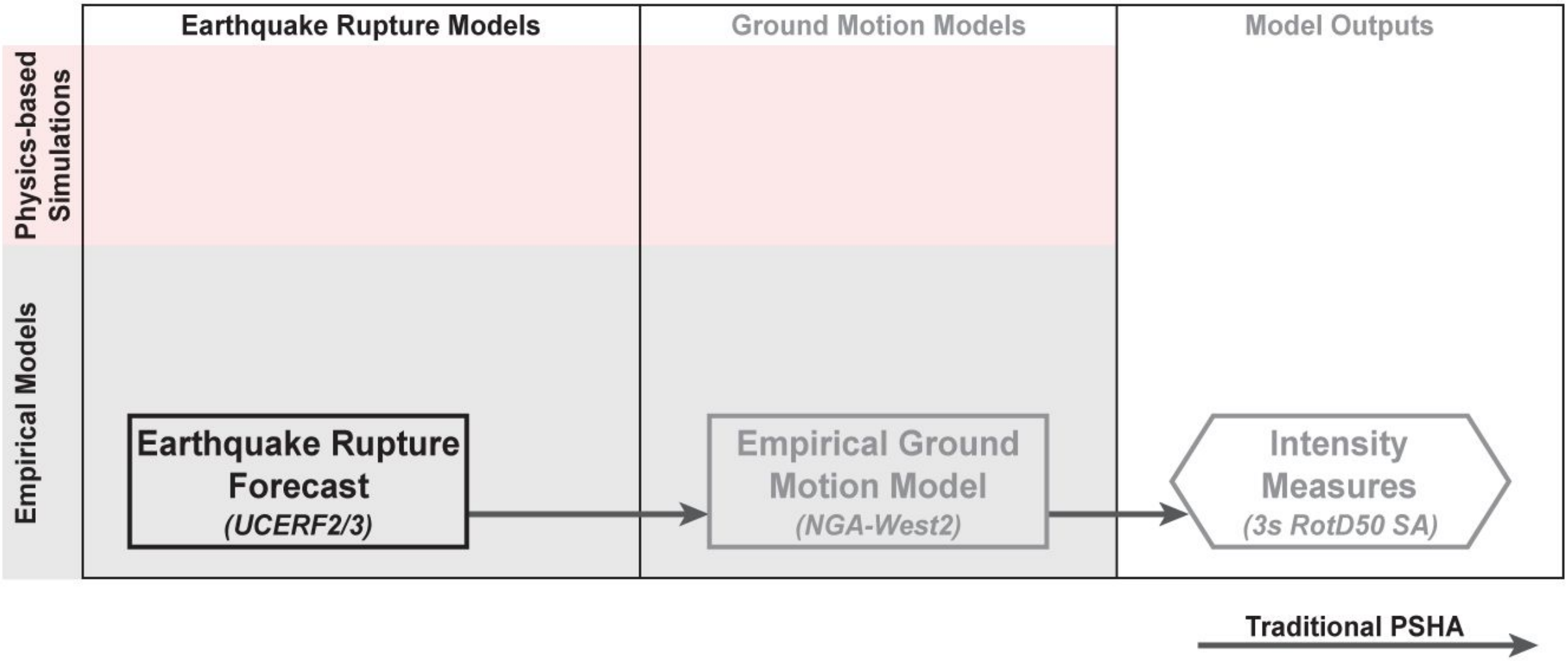
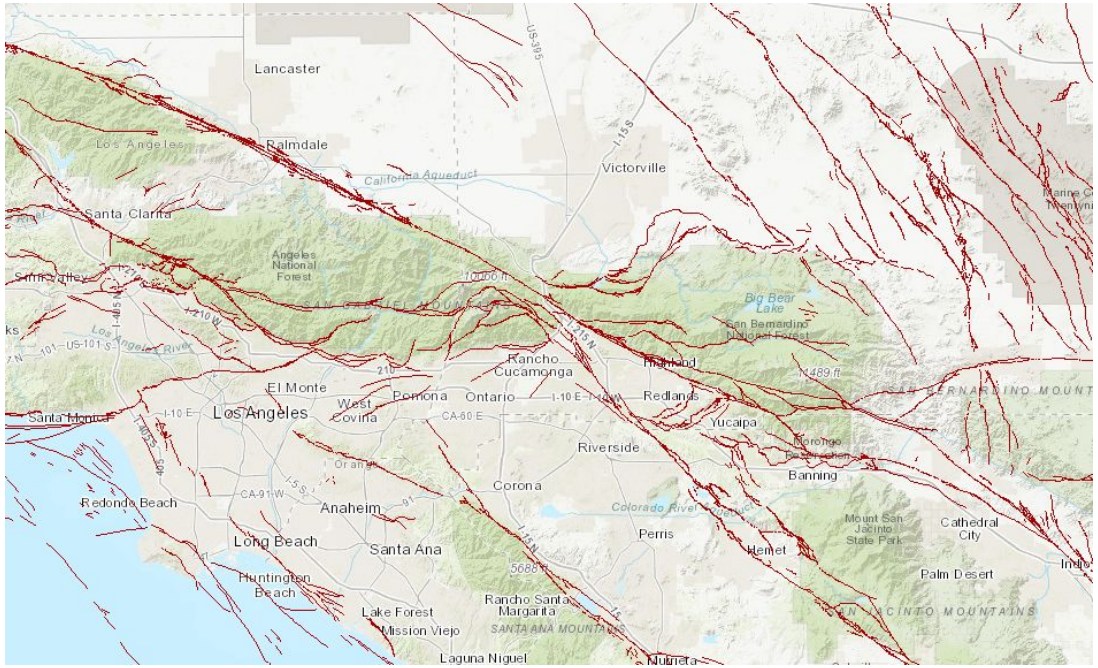


(Milner et al., 2021, *BSSA*)

Building an ERF With Few Observations

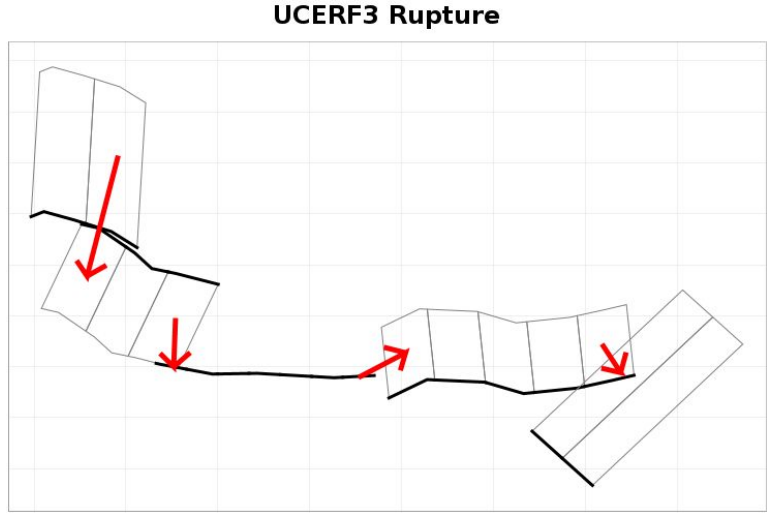
- Many mapped faults in California
- Limited historical observations of large earthquakes (~200 years)
- Some data constraints available:
  - Slip rate estimates
  - Paleoseismic recurrence studies
  - Observed seismicity
- Many assumptions required:
  - Fault magnitude-frequency distributions
  - Multi-segment & multi-fault ruptures?
  - Recurrence interval distributions
  - …many others

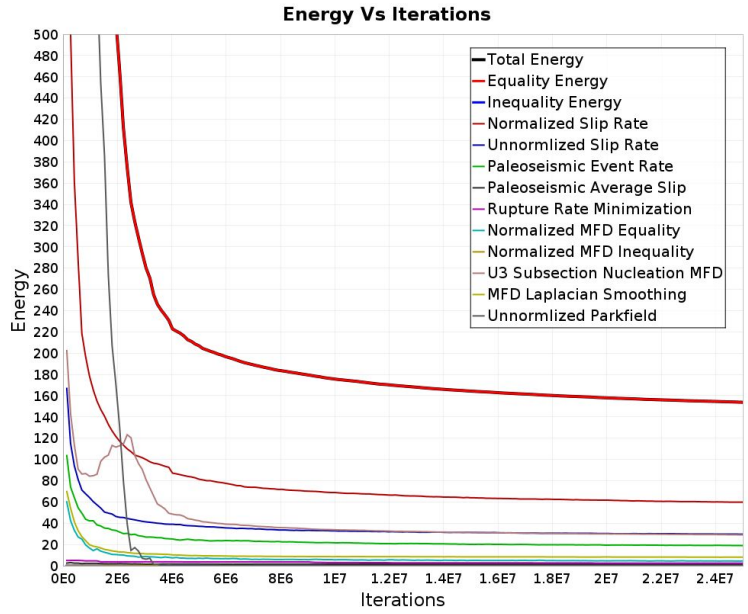


USGS Quaternary Faults (past 1.6 million years)

UCERF3 & NSHM23: Fault System Inversion

- Uniform California Earthquake Rupture Forecast (UCERF3)
  - Most recent published ERF for California
  - Solved for rupture rates through inversion
  - Includes multi-fault ruptures
- 2023 Update to the National Seismic Hazard Model (NSHM23)
  - Improves upon UCERF3, extends inversion methodology to WUS active faults
- Better data fits than prior models, but highly uncertain and many assumptions
- See: Field, Milner, and Page (2021)





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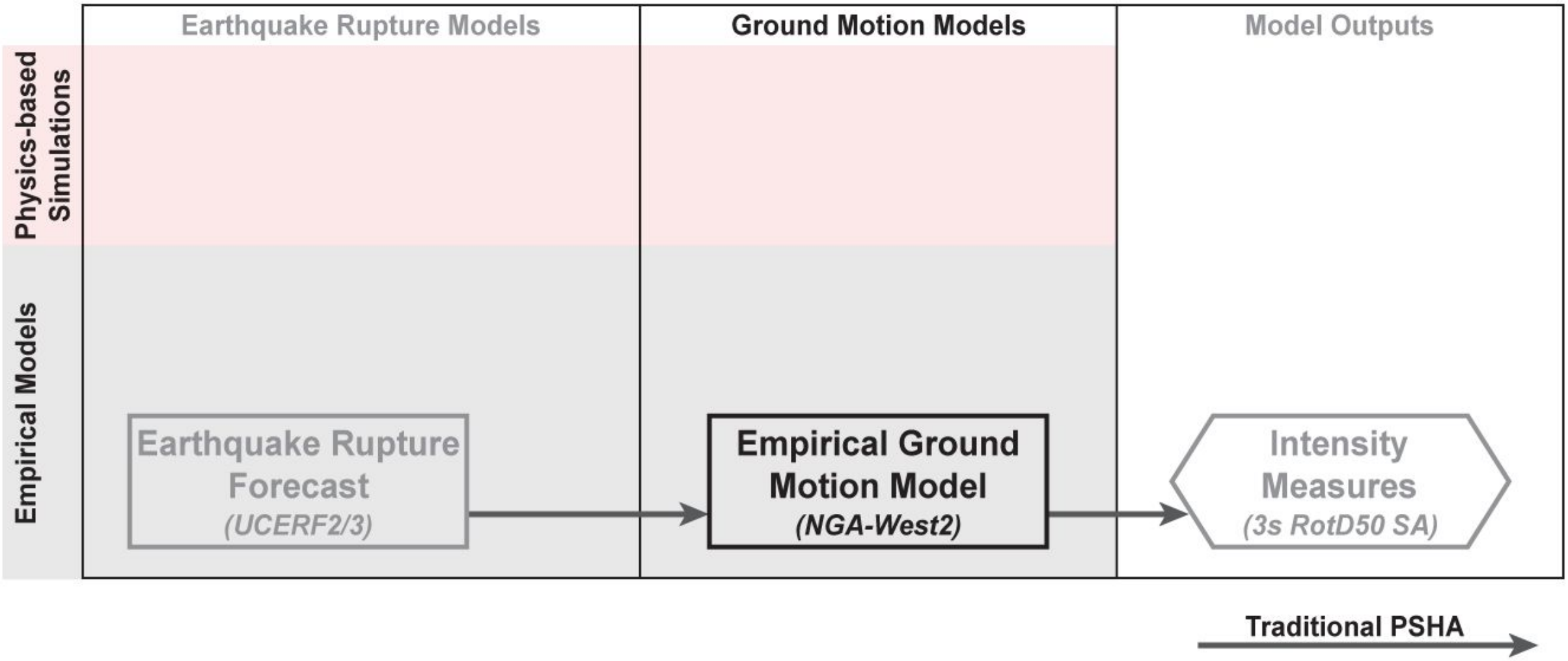
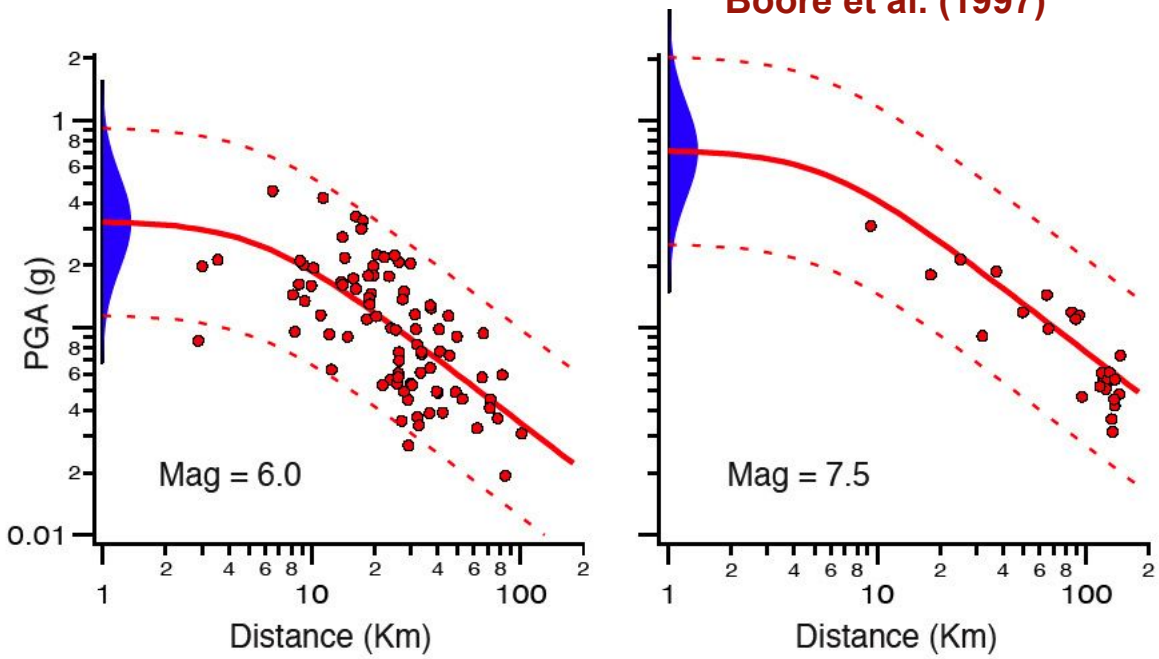


(Milner et al., 2021, *BSSA*)

Empirical Ground Motion Models

- Estimate the log-mean and standard deviation of shaking at a site of interest, conditioned on the occurrence of an earthquake
- Regress against observations
  - Rupture-site distance
  - Magnitude
  - Site effect proxies
    - V_{S30}, $Z_{1.0}$, $Z_{2.5}$
  - Fault type
    - strike-slip, normal, reverse

Boore et al. (1997)



Courtesy of Ned Field

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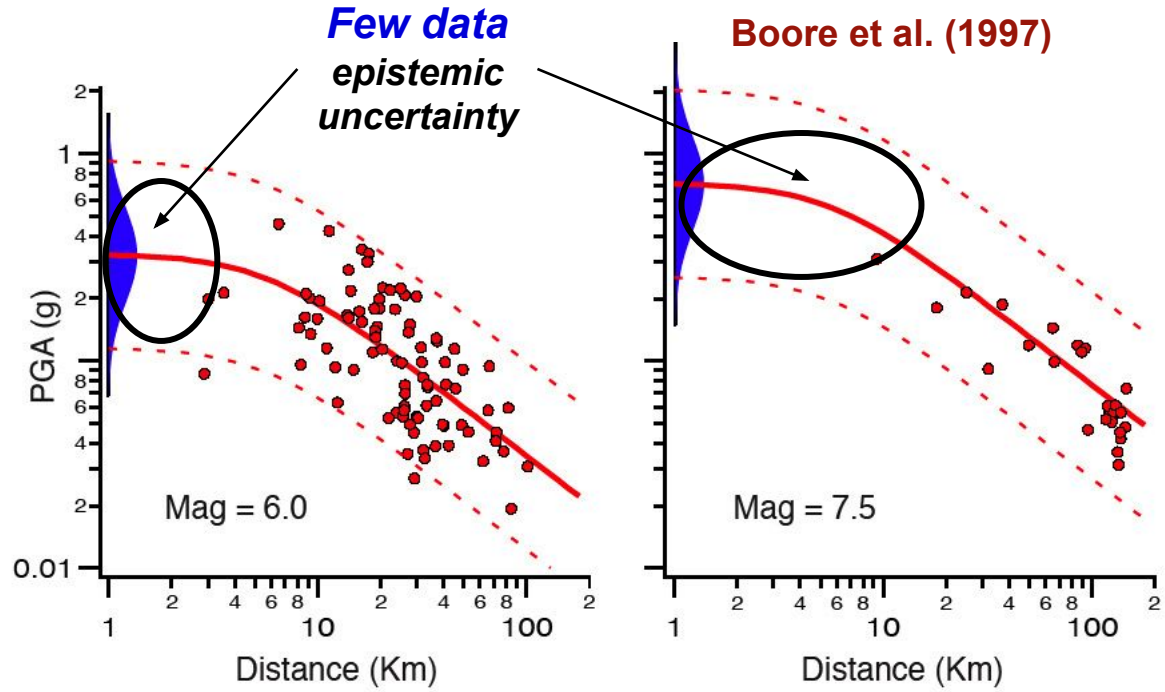
- Few data at short distances and large magnitudes, high scatter



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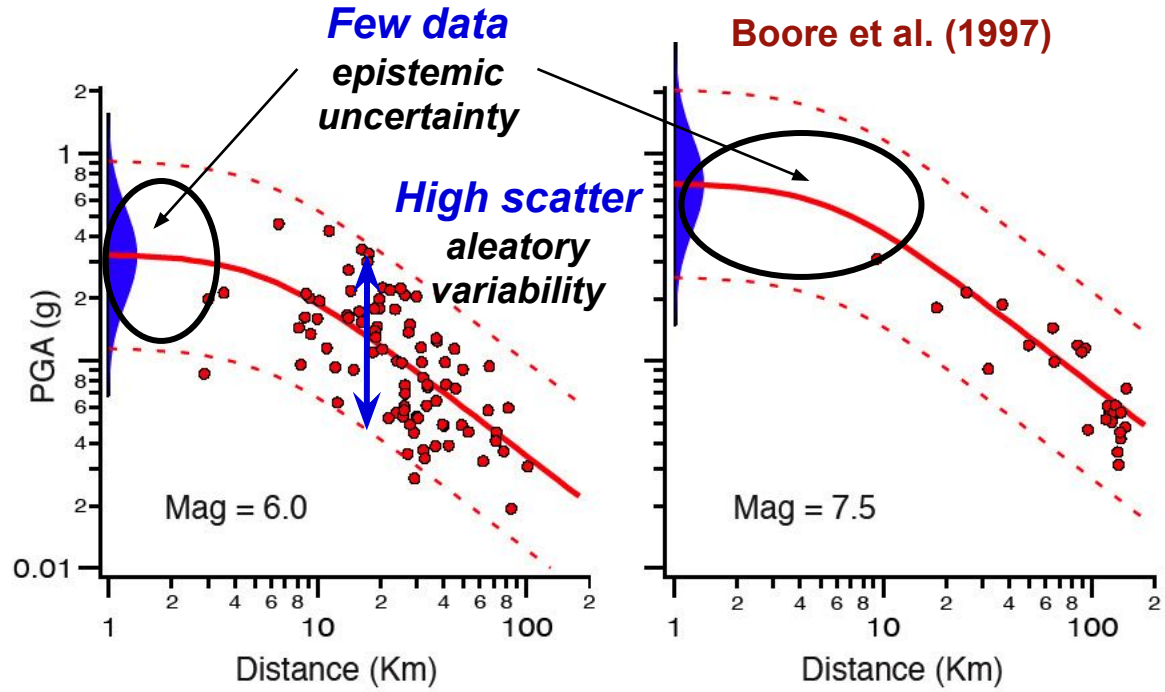
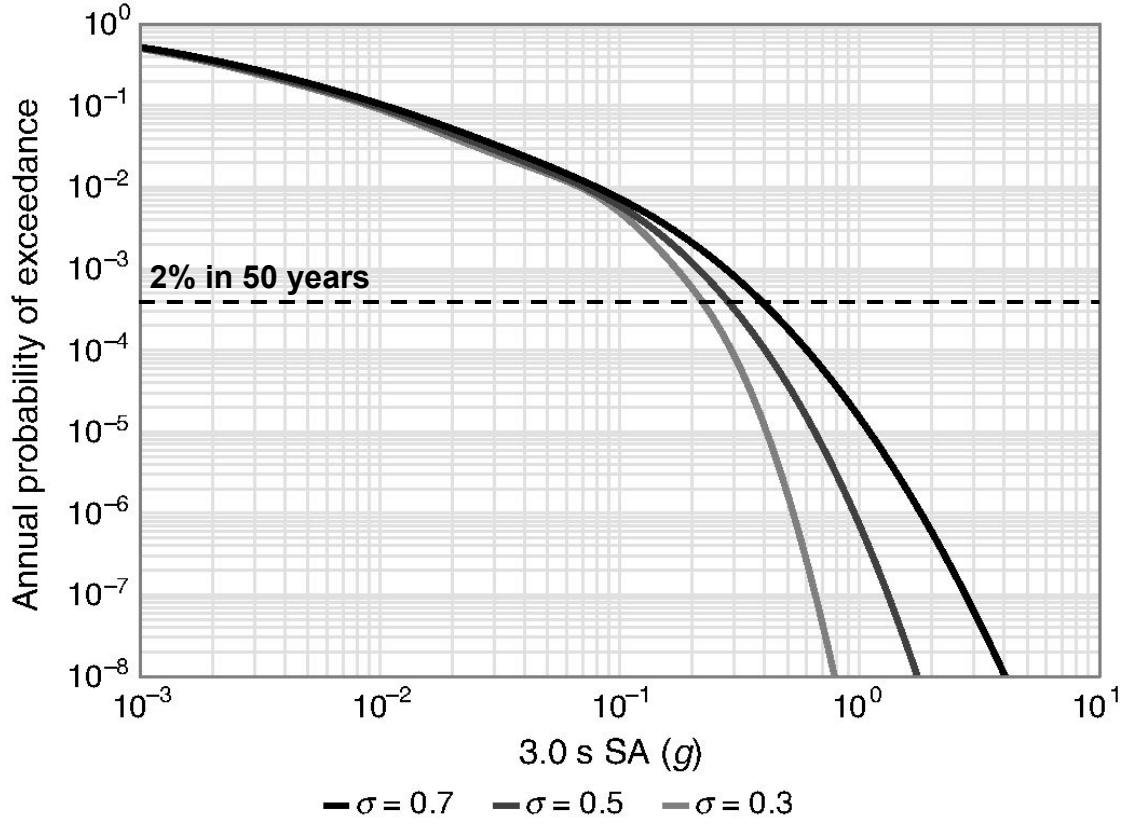


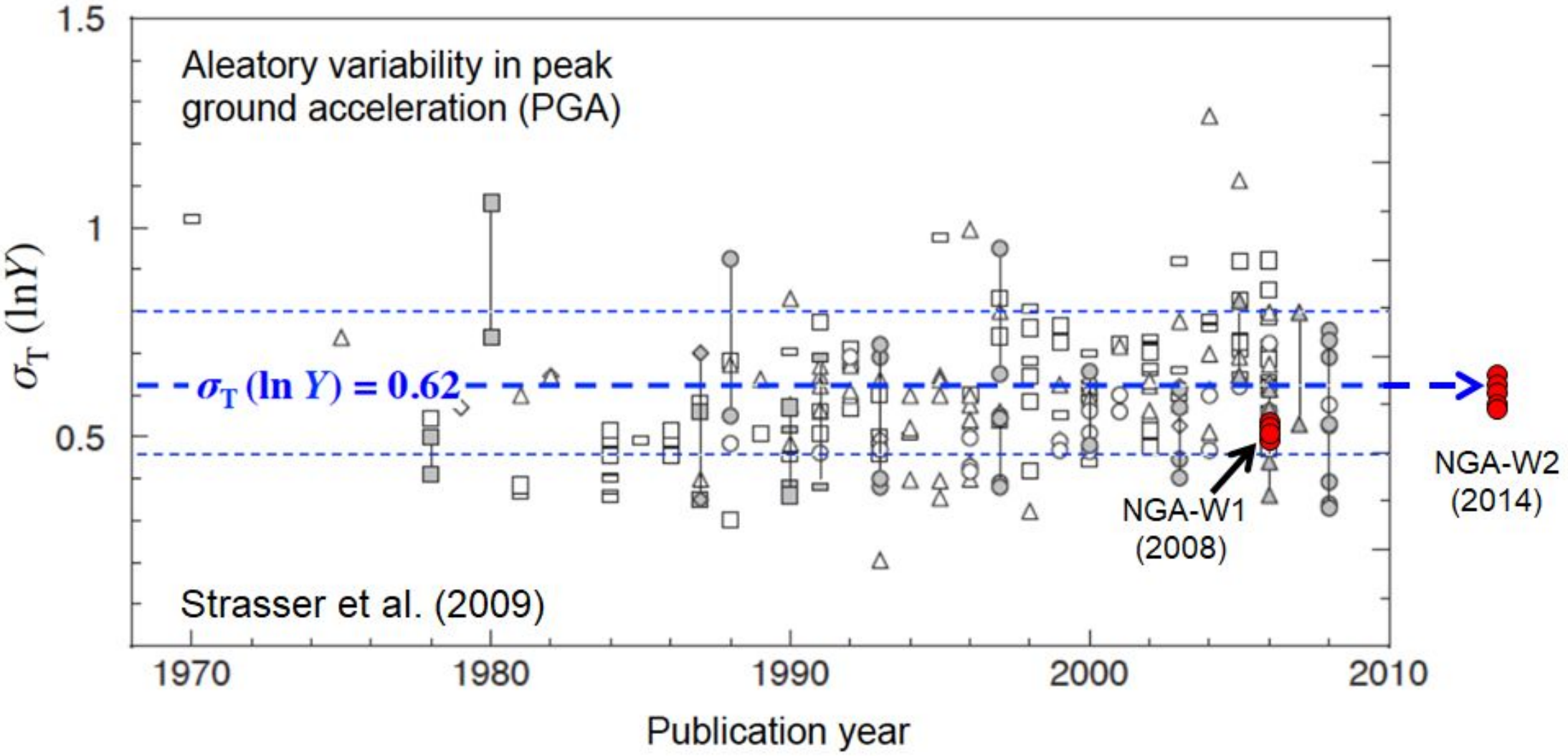
Courtesy of Ned Field

Hazard Curves & σ-dependence

- Hazard curves are key output of PSHA
  - probability of exceeding (y-axis) various ground motions levels (x-axis)
  - Aggregate contributions from all sources in the ERF
- Tails of hazard curves are controlled by ground motion uncertainty
  - Hazard at typical 2% in 50 year return period is very sensitive to σ



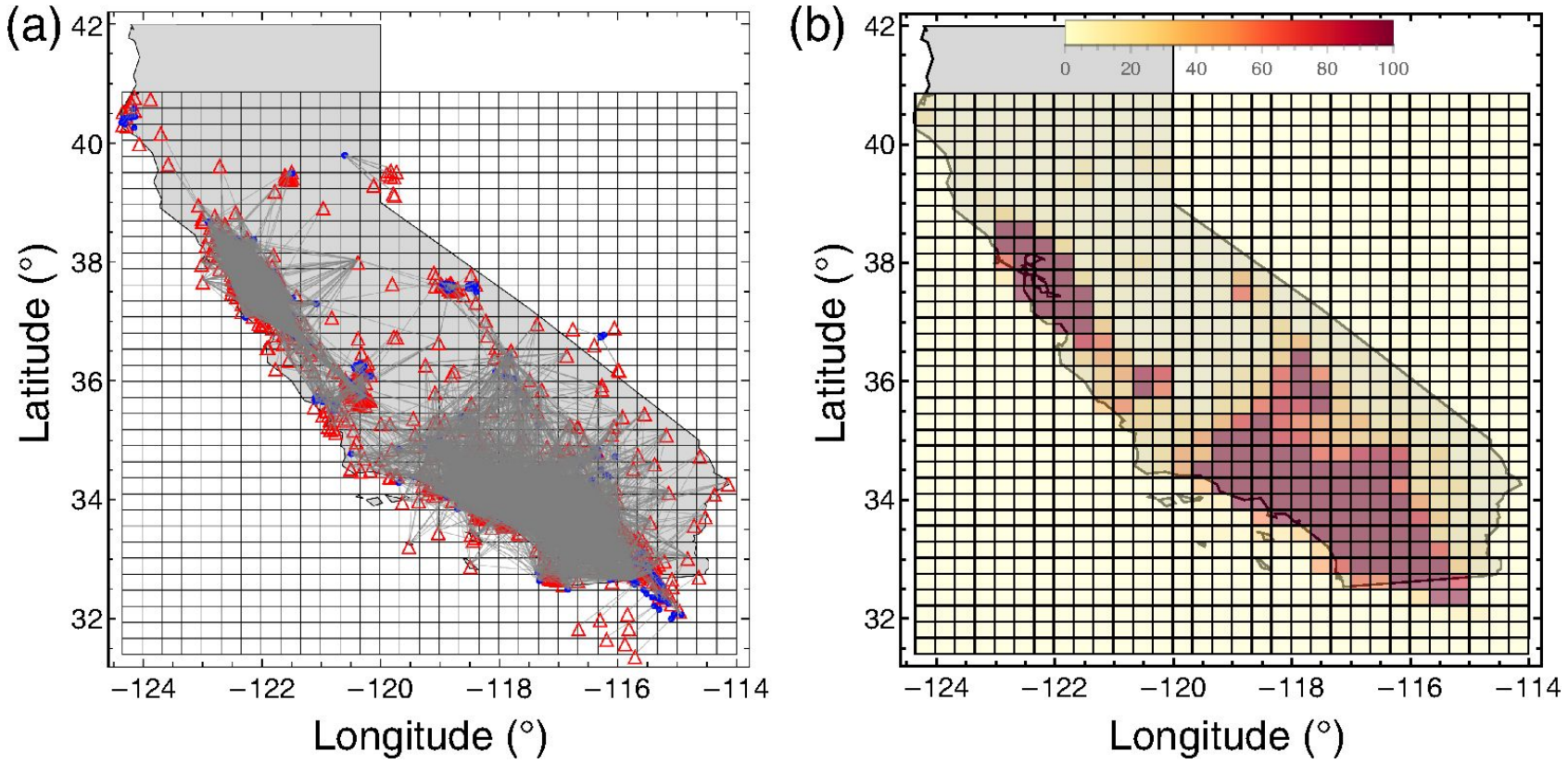
Sigma Over Time



Strasser et al. (2009), annotated by Tom Jordan

Empirical Nonergodic PSHA

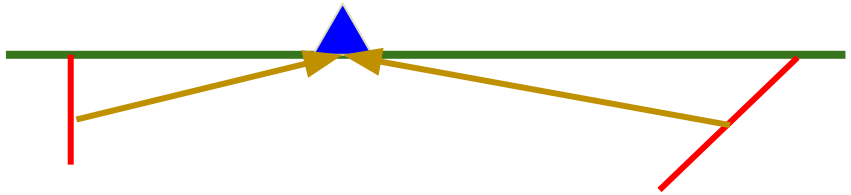
- Work is underway to reduce σ in well instrumented areas
- Difficult to extrapolate to large earthquakes that dominate hazard

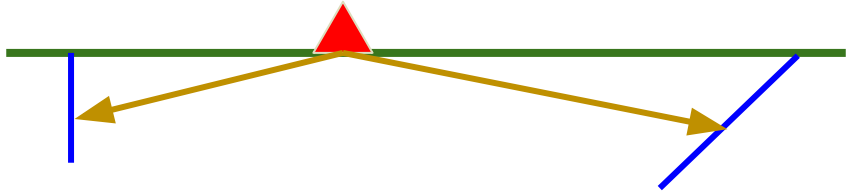


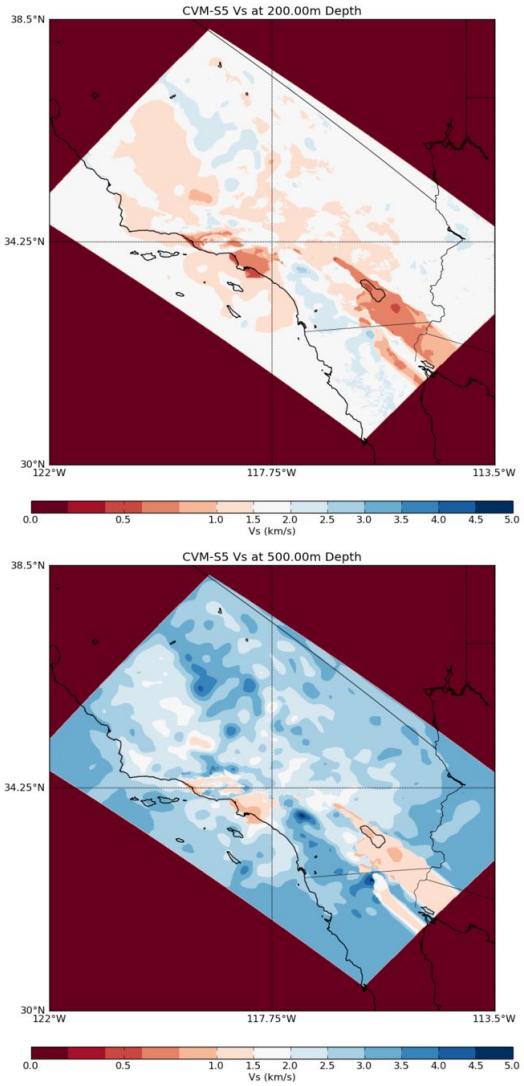
Abrahamson et al., 2019

CyberShake 3D Deterministic Simulations

- Deterministic 1 Hz simulations in a 3-D velocity model
  - ADP-ODC-GPU simulation code
  - SCEC CVM-S4.26-M01 velocity model
- CyberShake uses seismic reciprocity
  - Impulse is positioned at site (2 3D simulations to recover x and y component) and recorded at each source patch
  - Useful when $\mathbf{N}_{sites} << \mathbf{N}_{ruptures}$
  - Assumes linearity

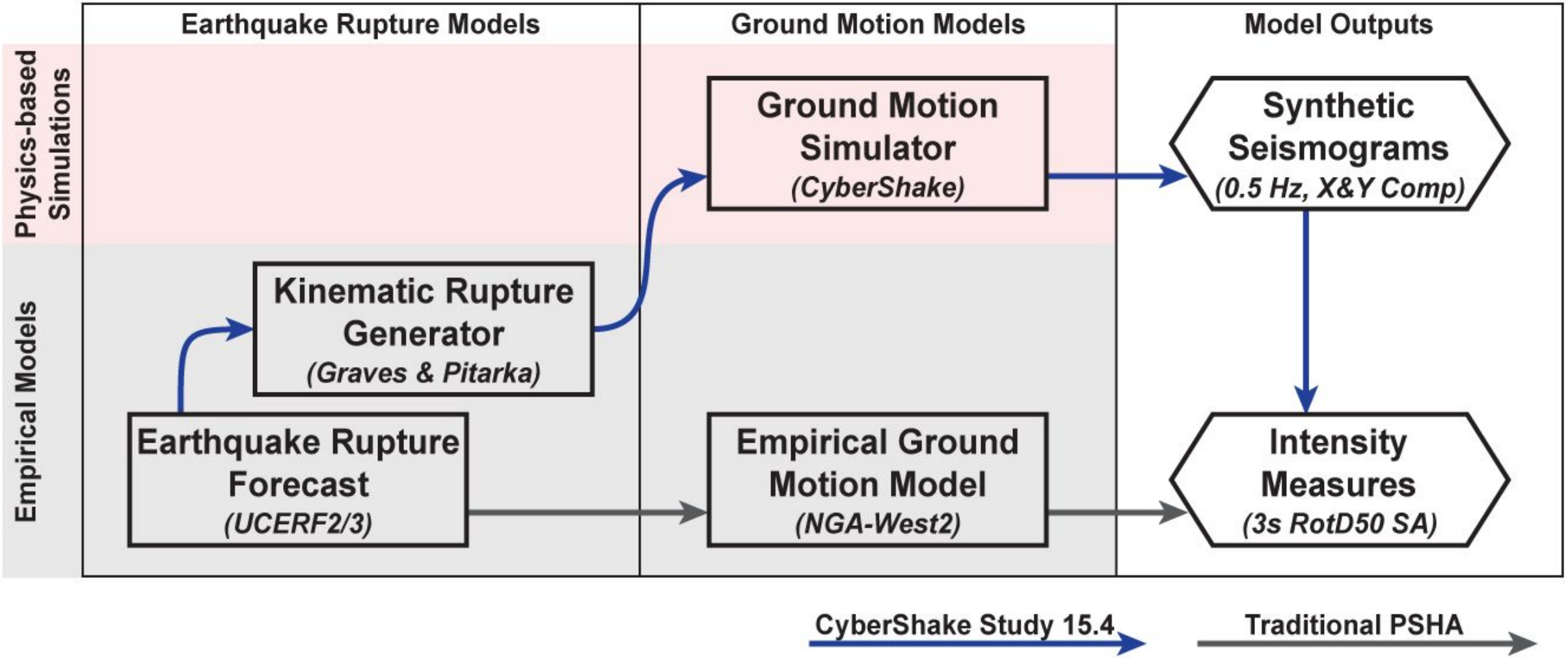






CVM slices from Mei-Hui Su

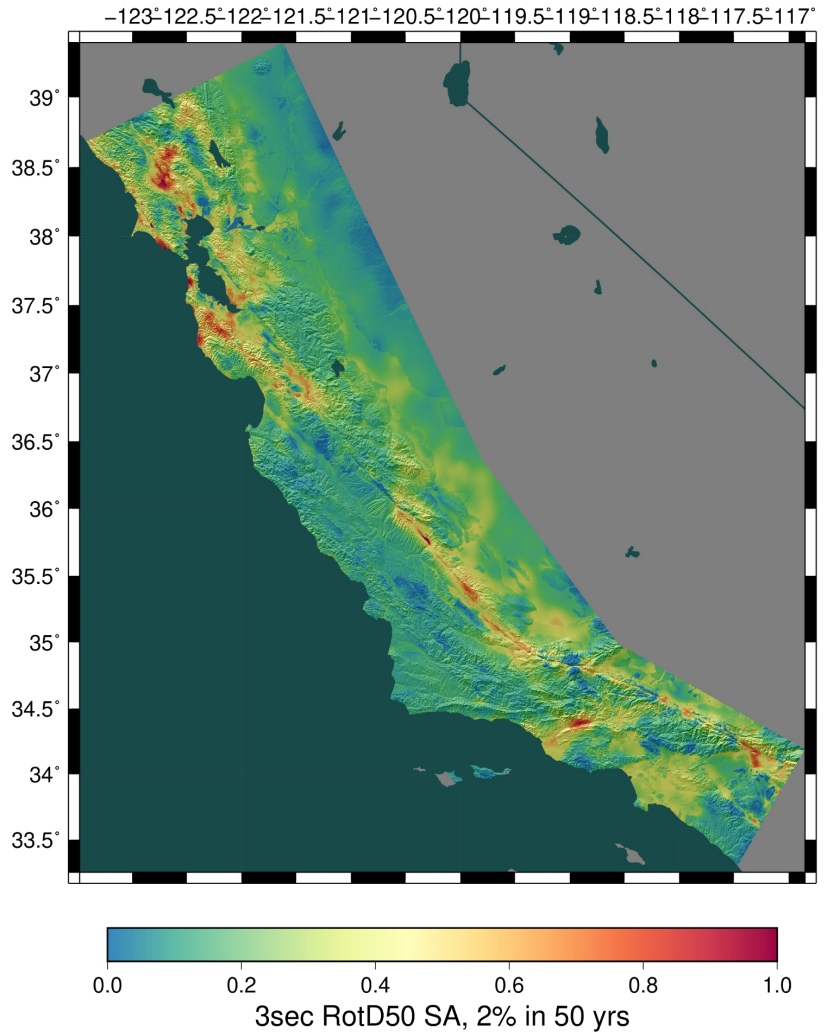
PSHA Pathways



(Milner et al., 2021, *BSSA*)

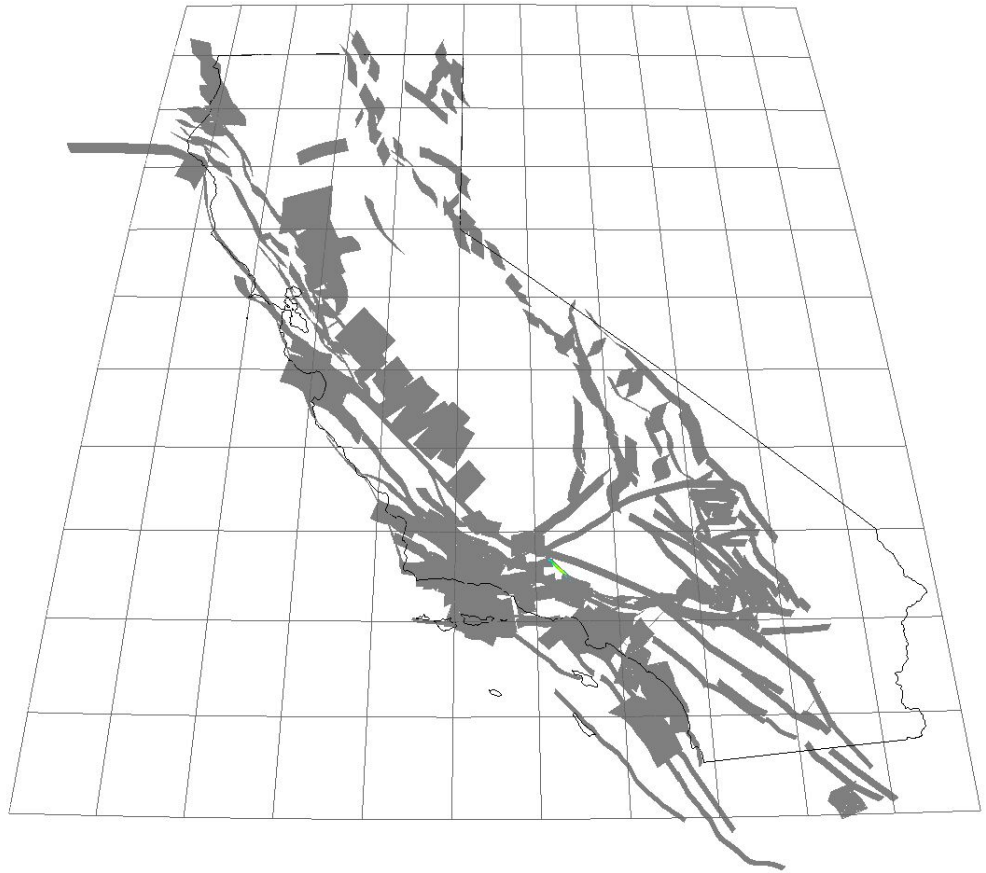
Traditional CyberShake Studies

- Extend empirical ERFs with a kinematic rupture generator
  - Graves & Pitarka (2010, 2014, 2016)
- UCERF2 ERF
  - Does not currently support multi-fault ruptures from UCERF3
- Extract intensity measures from synthetic seismograms to compute hazard curves



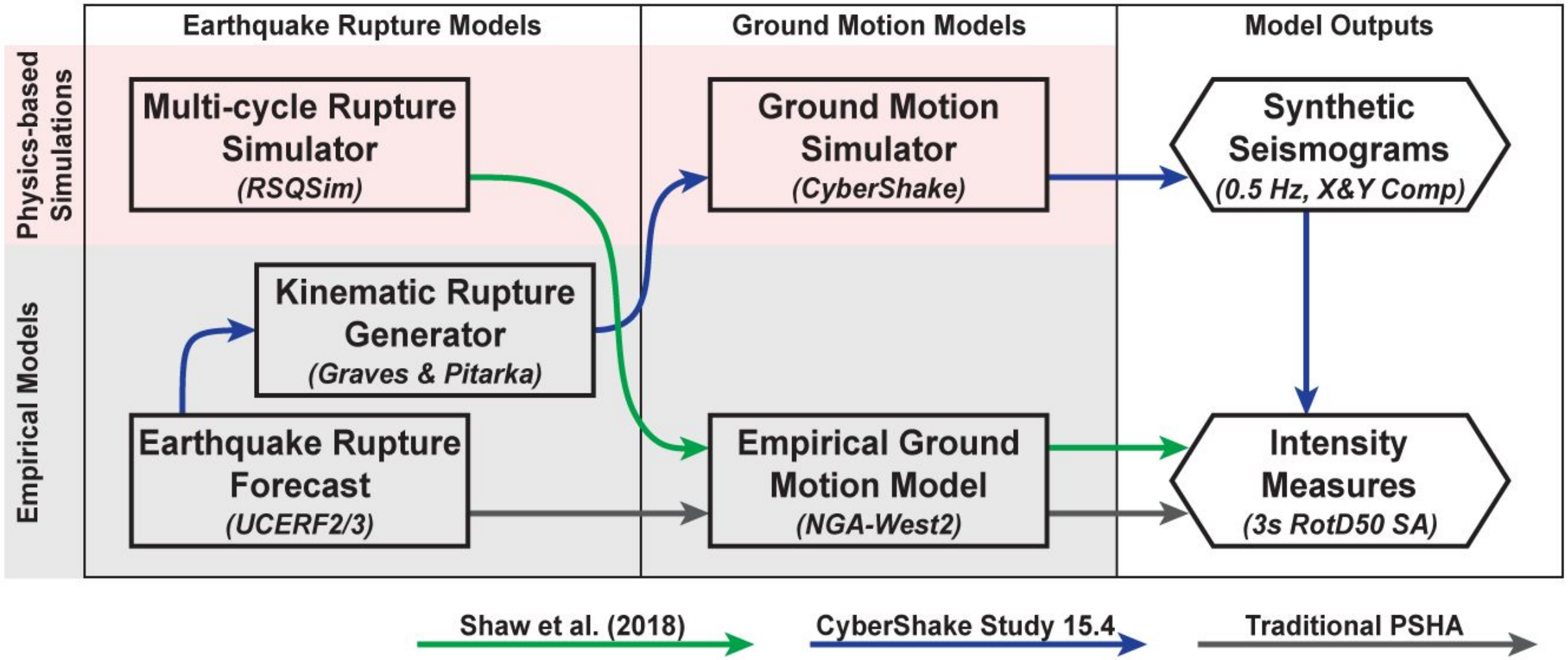
A Different Approach: RSQSim

- **R**ate **S**tate earth**Q**uake **Sim**ulator
  - Richards-Dinger & Dieterich, 2012
- Physics-based multi-cycle simulator
  - Tectonic loading of faults by backslip approximation
  - Rupture nucleation by rate- and state-dependent friction
  - Dynamic overshoot
  - Stress transfer in homogeneous elastic halfspace
- No prescribed ruptures/MFDs
- Synthetic catalogs of thousands to millions of years of earthquake sequences



Animation of 3,000 years of RSQSim ruptures in CA
(100 years per second)

PSHA Pathways



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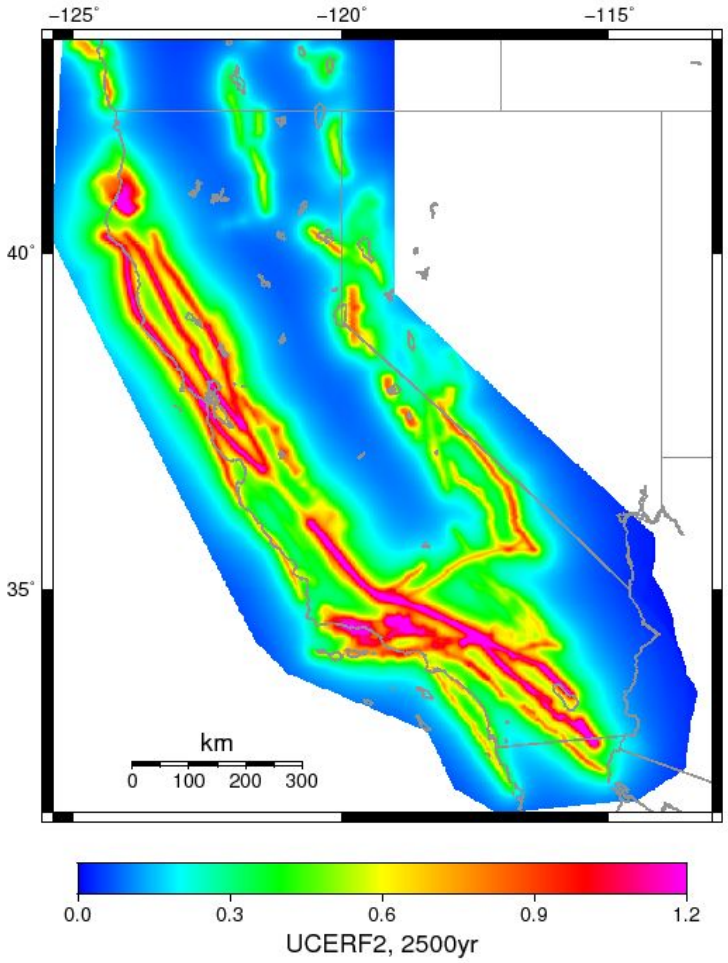
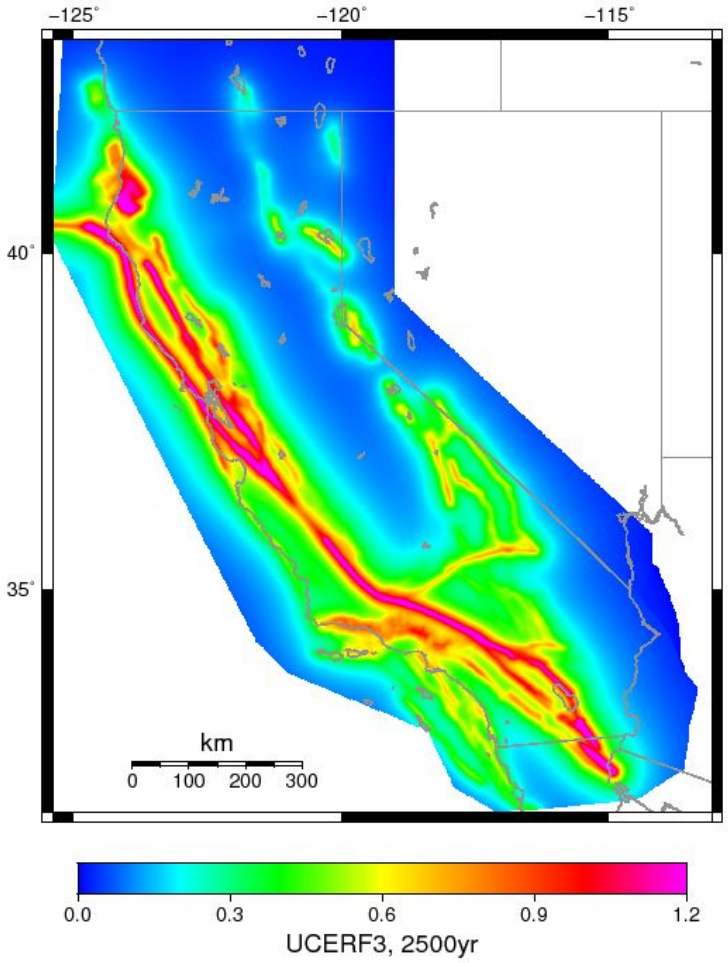
GMM Hazard Maps Comparison

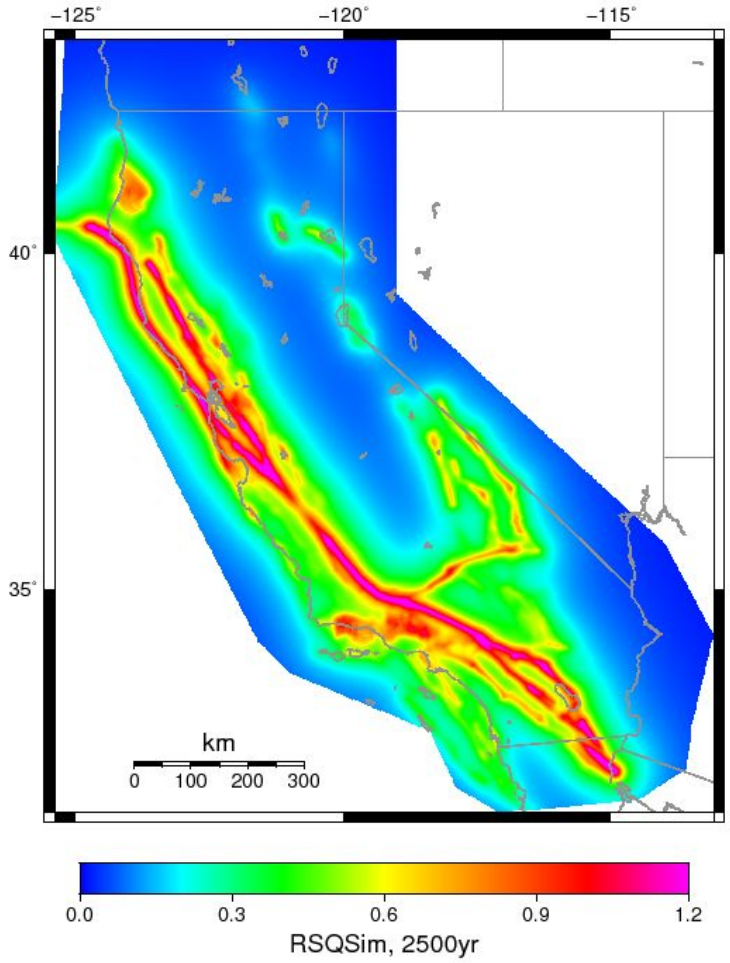
UCERF2



UCERF3



RSQSim



Peak Ground Acceleration (g) with 2% probability of exceedance in 50 years **(Shaw et al. 2018, *Science Advances*)**

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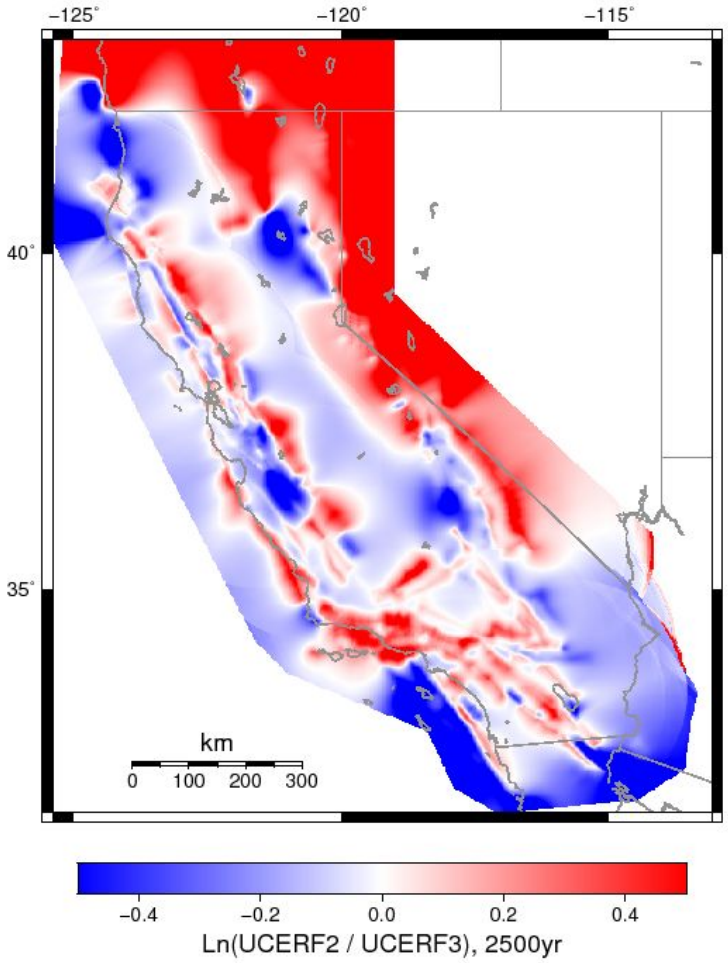

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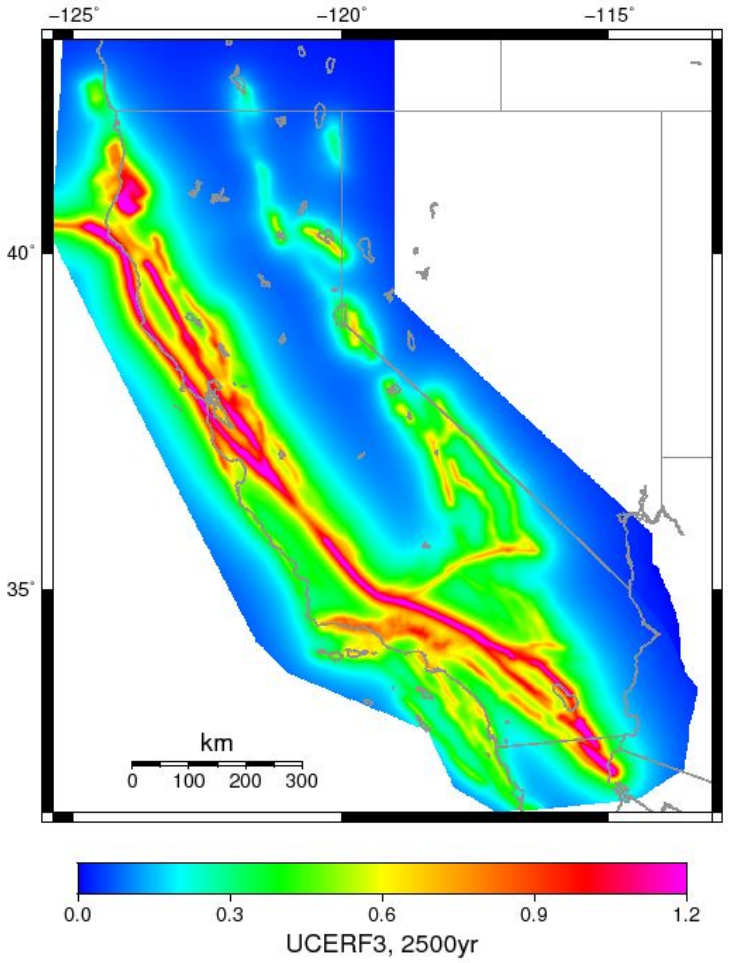
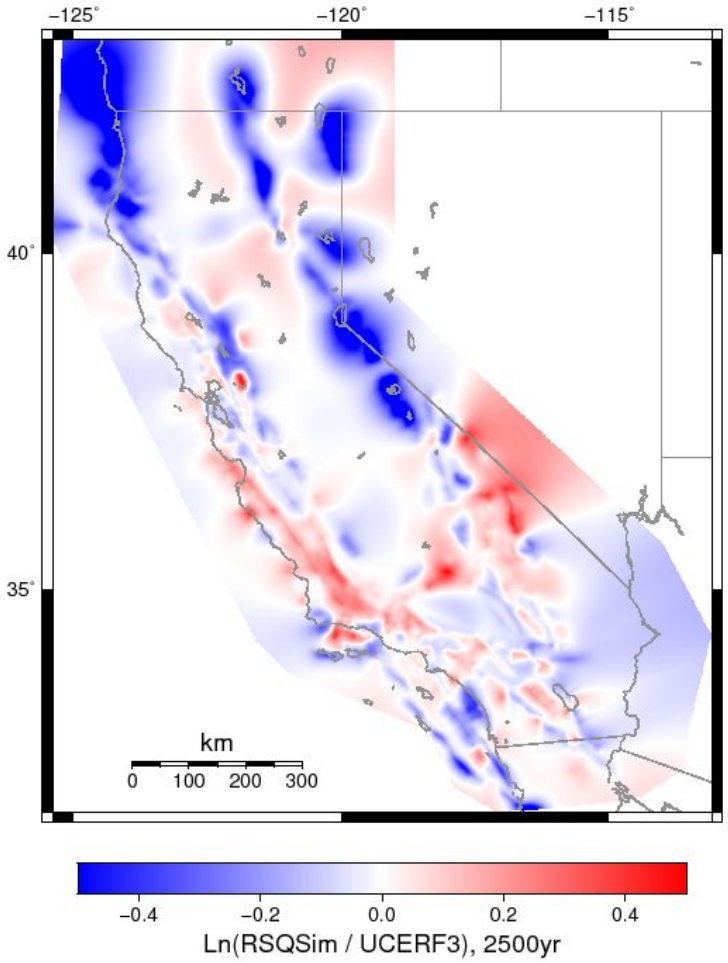


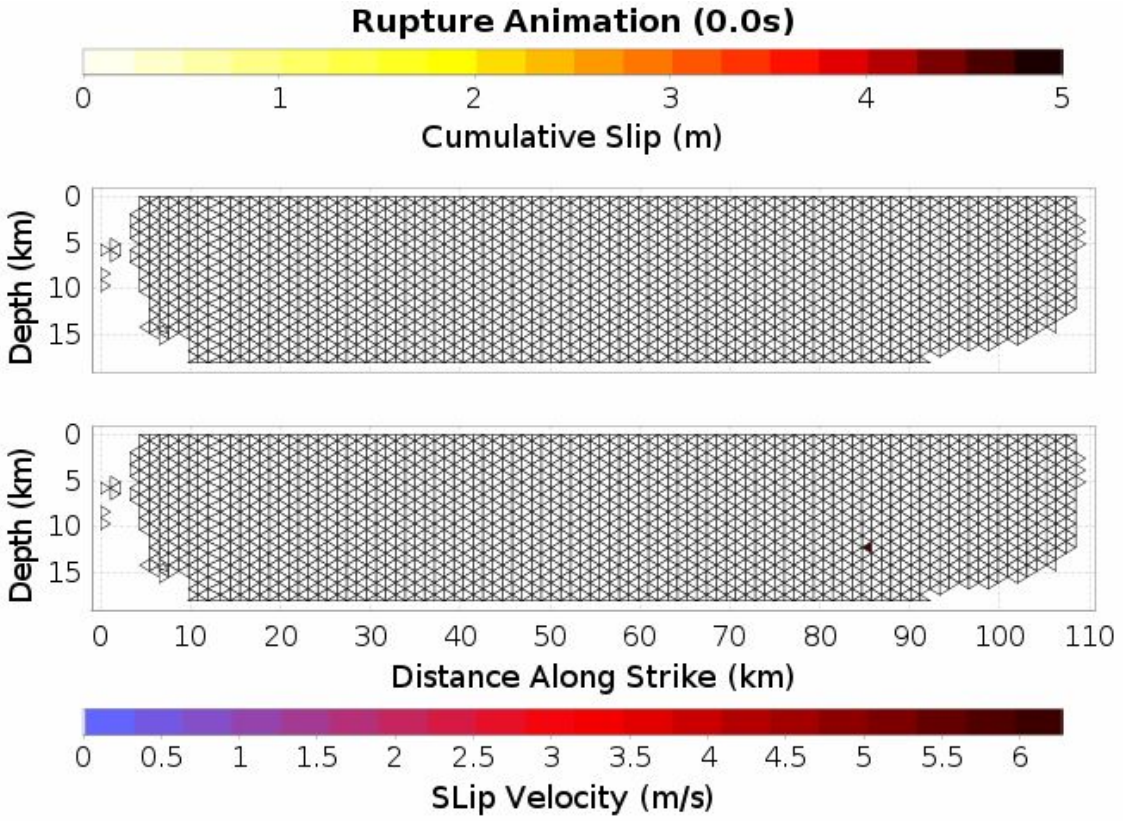
RSQSim



Peak Ground Acceleration (g) with 2% probability of exceedance in 50 years **(Shaw et al. 2018, *Science Advances*)**

RSQSim Rupture Slip-Time Histories

- RSQSim provides full slip-time histories for all ruptures
  - Example (right): M7.45 on SAF Mojave
- Can be used directly as input to deterministic ground motion simulations
- Unlike kinematic rupture generators, no prescribed rupture properties
  - Stress drop, hypocenter, roughness, etc, dependent on global frictional parameters and state of stress at nucleation



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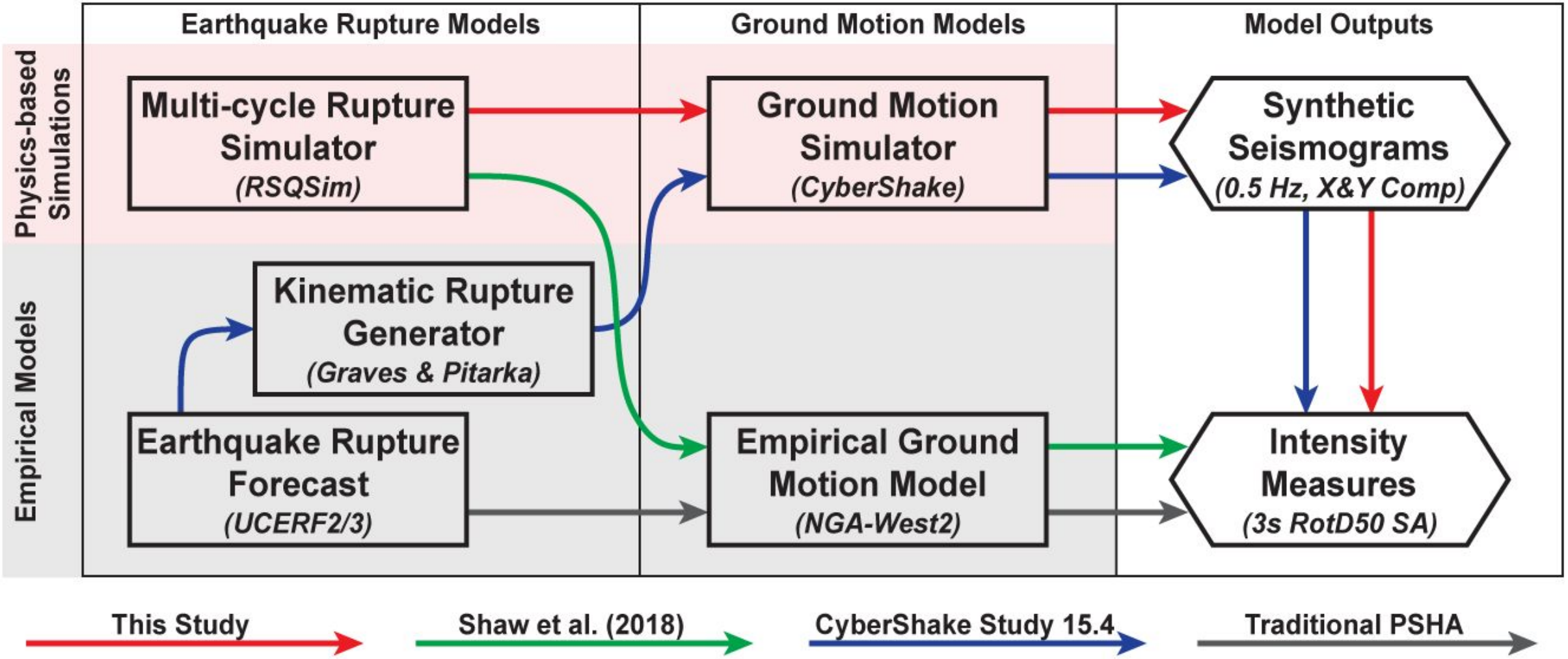
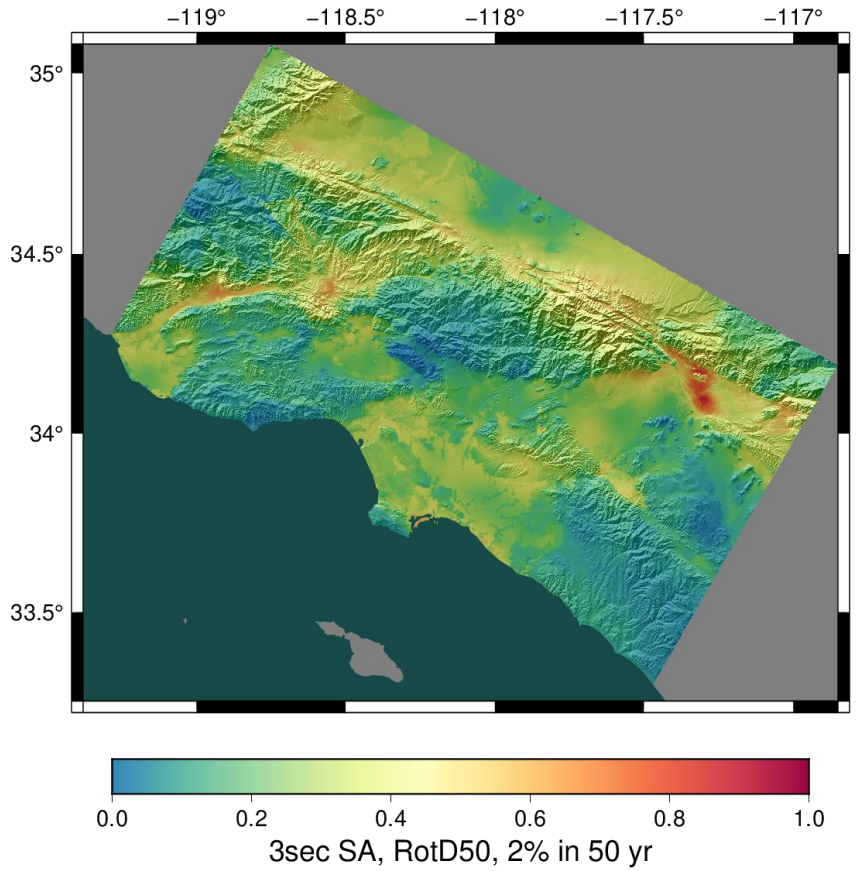


(Milner et al., 2021, *BSSA*)

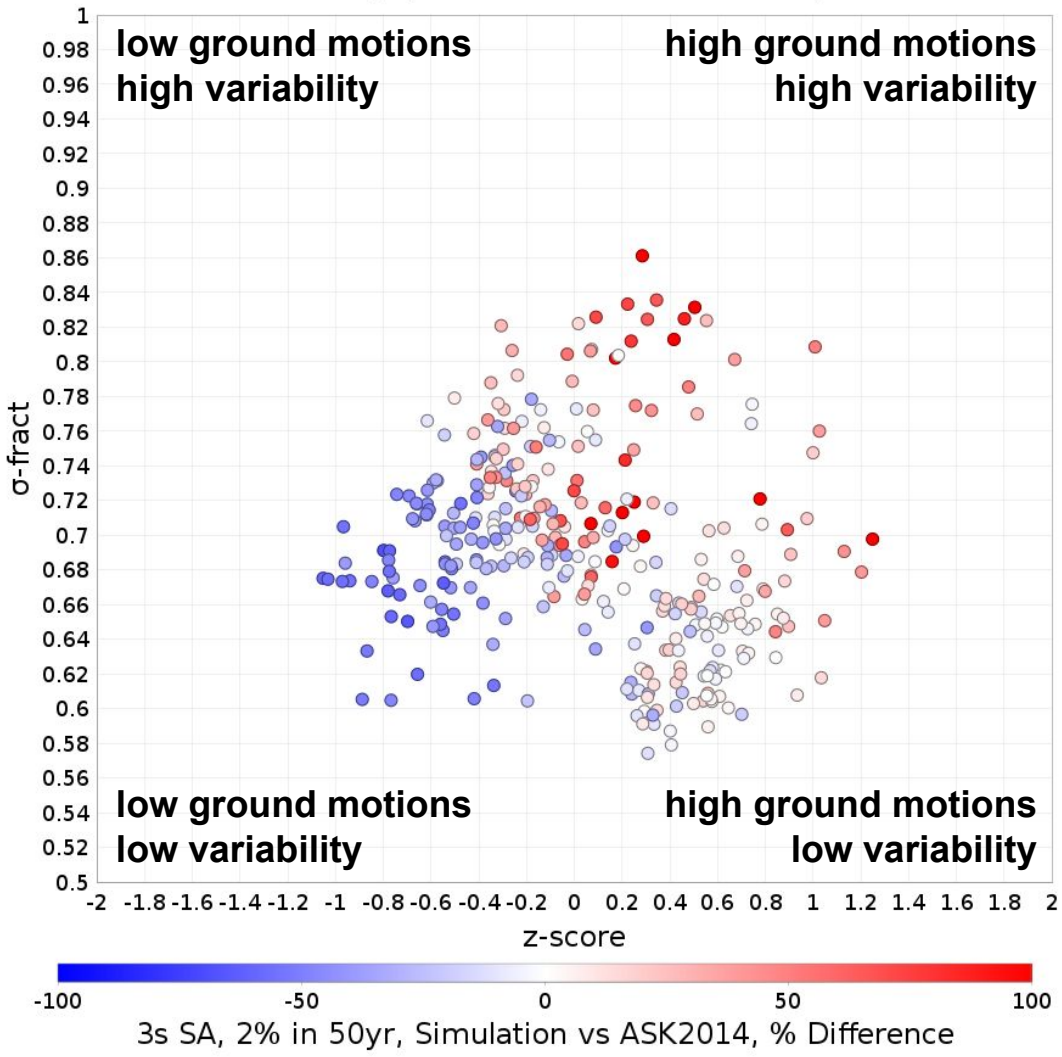
Regional Hazard Map

- First hazard map constructed with physics-based models
  - RSQSim source model
  - CyberShake ground motion simulation
- Study performed over 29 days
  - Used OLCF *Summit* supercomputer
- 65,500 node-hours used
  - At peak, 46% of *Summit*
- Prototype study: Milner et al. (2021)

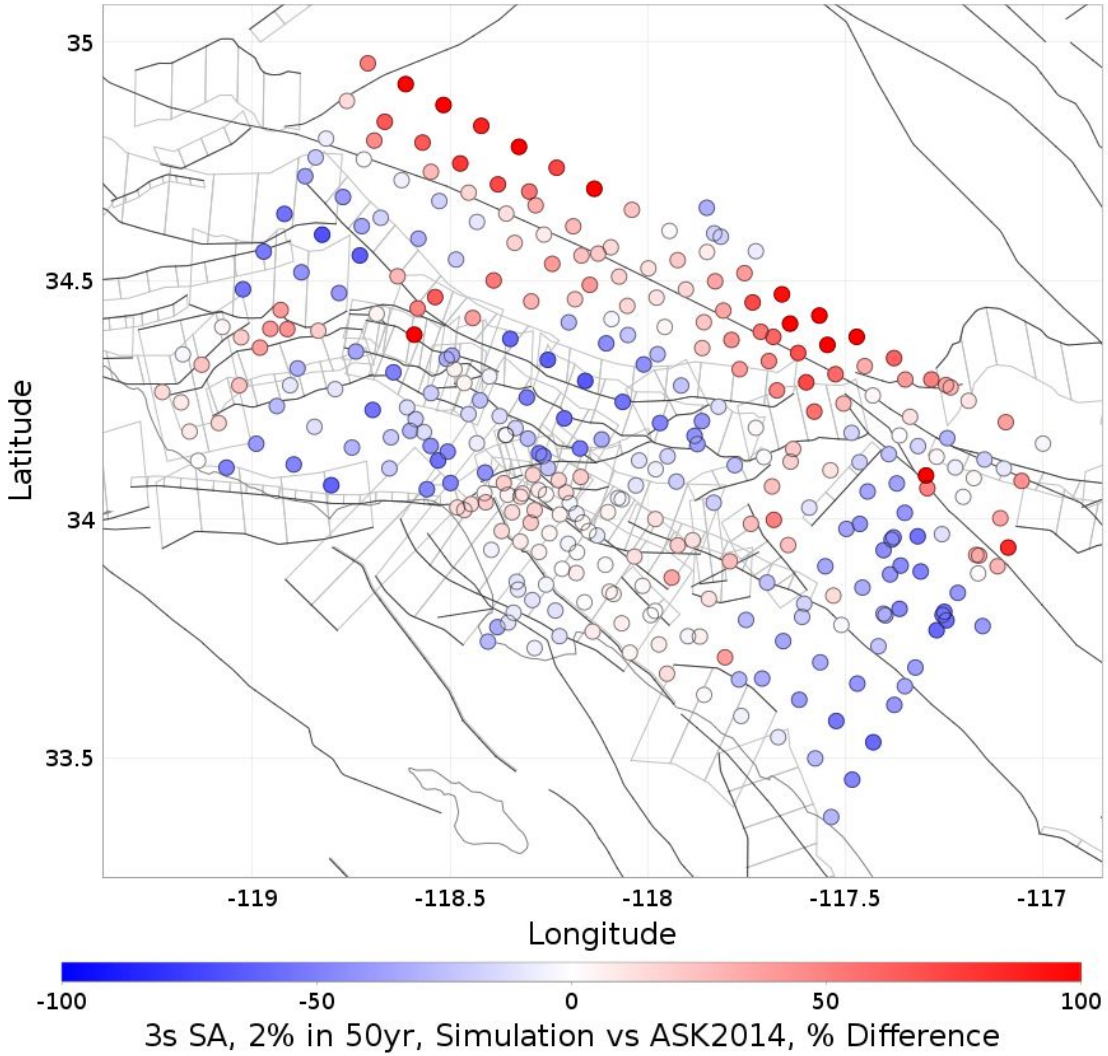


Hazard & Variability

Site z-scores, σ-fracts, and hazard



Hazard Comparison

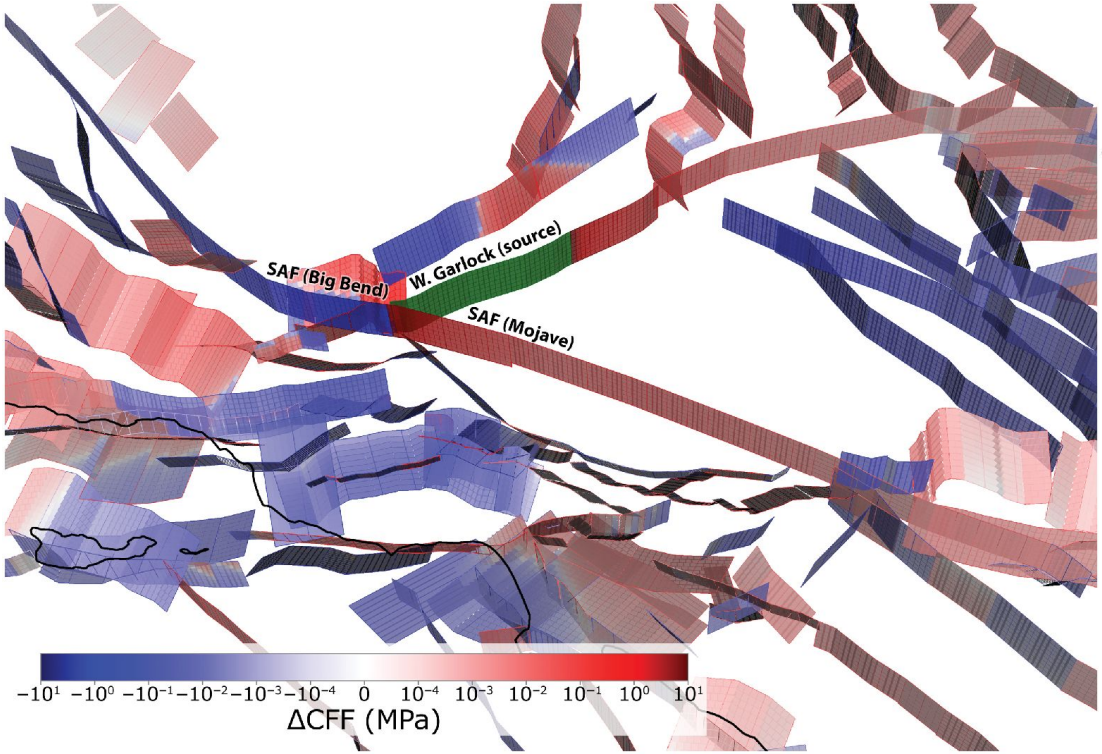


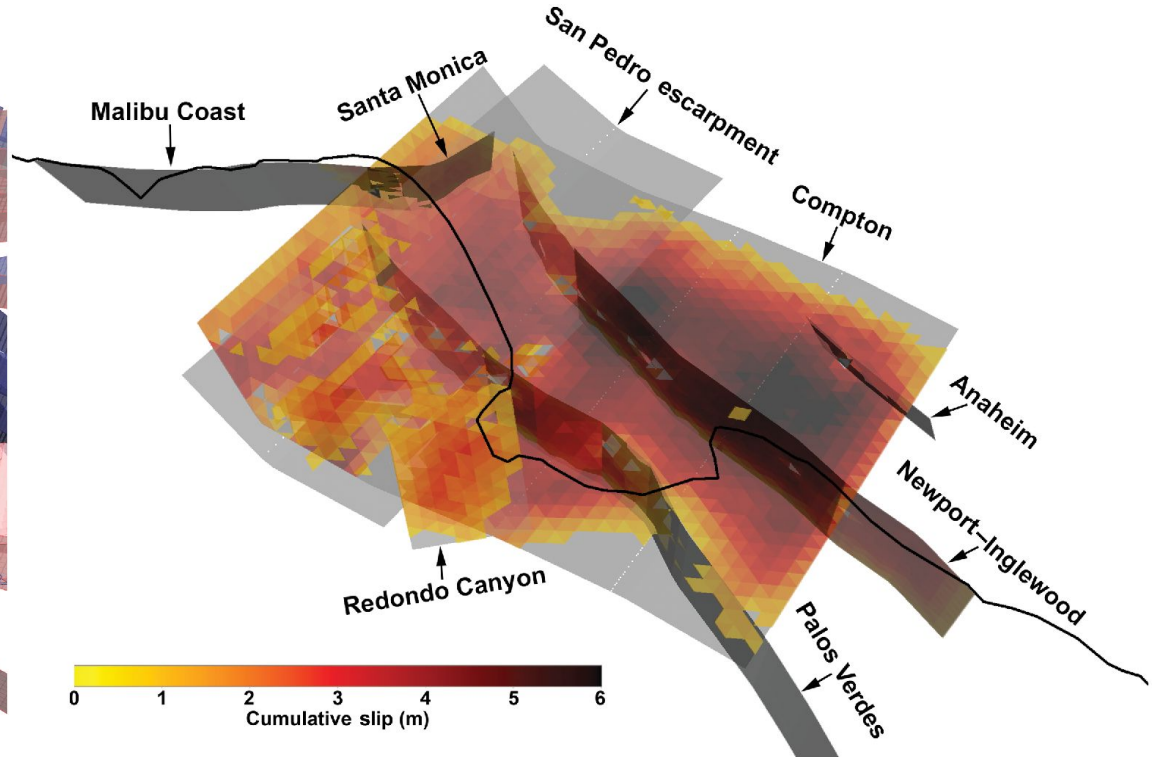
Simulations Are Informing Current Models

- Even if not ready for direct use, simulation-based comparison models are already valuable when building empirical models
  - Even if they're "wrong" they can be useful
- **Most useful if they work at the same regional and time scales as empirical models**

Simulations Are Informing Current Models

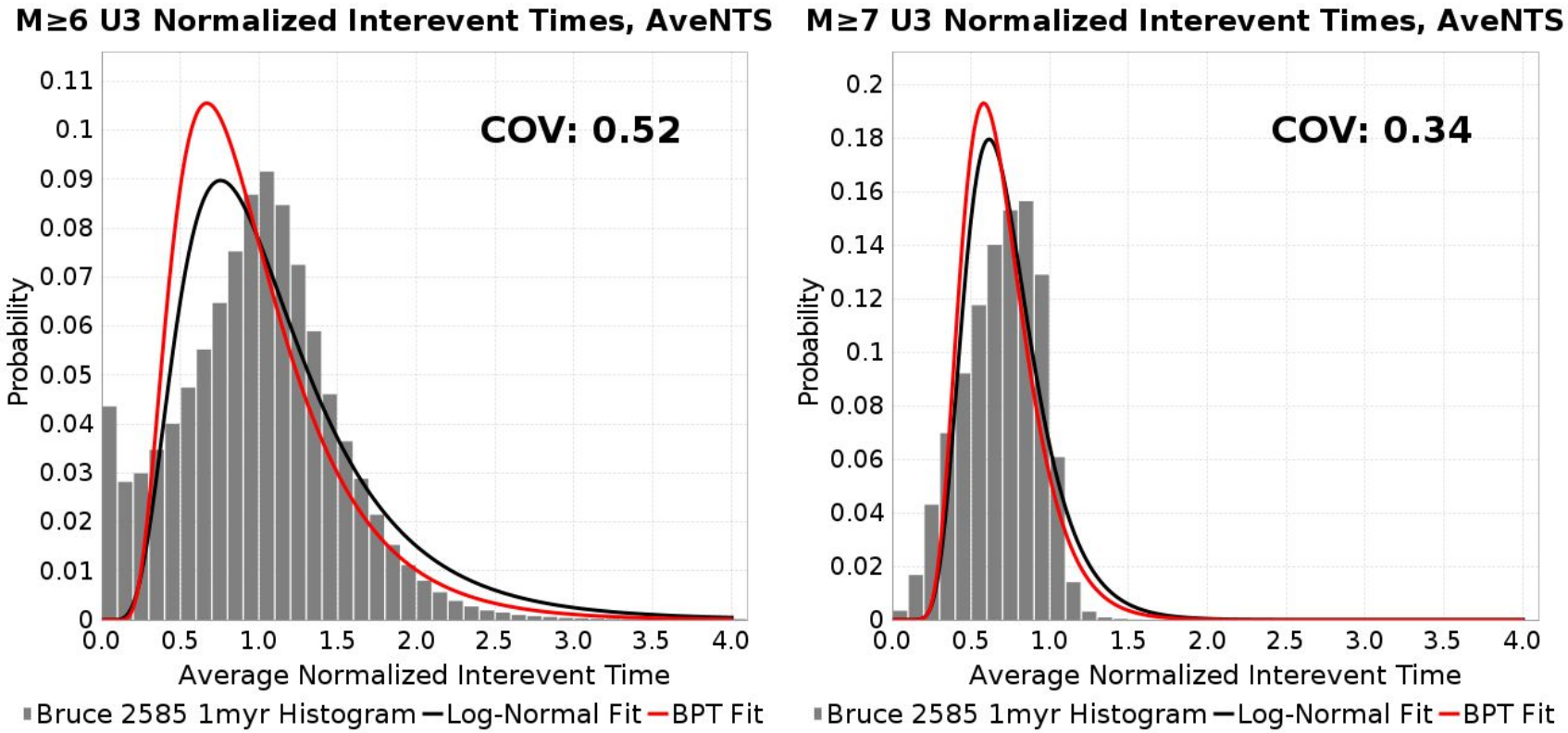
- RSQSim used to inform multifault rupture plausibility model for NSHM23
  - Milner et al. (2022)





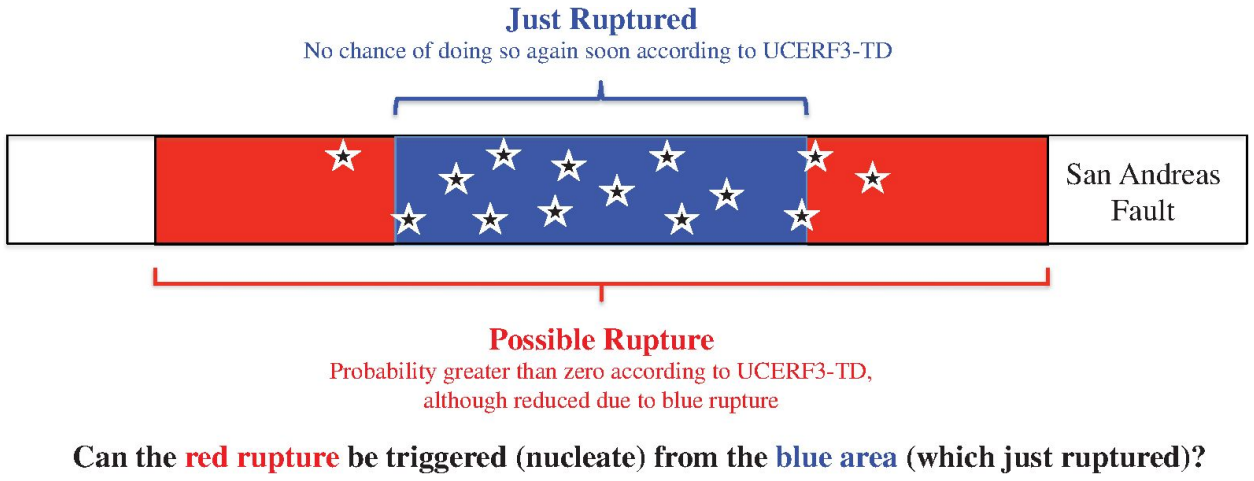
Simulations Are Informing Current Models

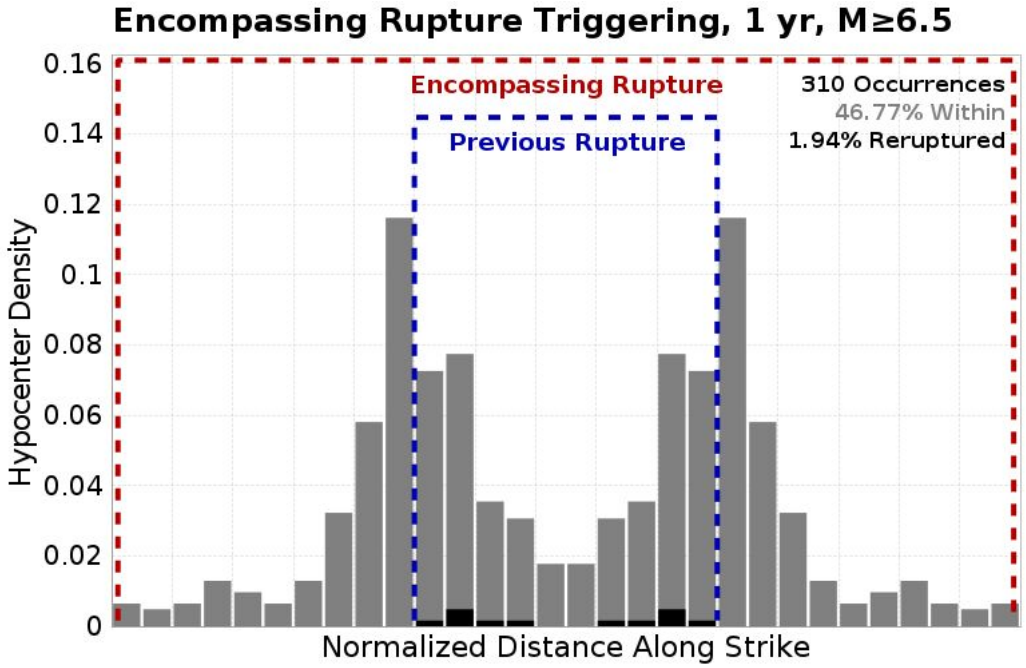
- Magnitude-dependent elastic rebound aperiodicity informed UCERF3-TD
  - Field et al. (2015)



Simulations Are Informing Current Models

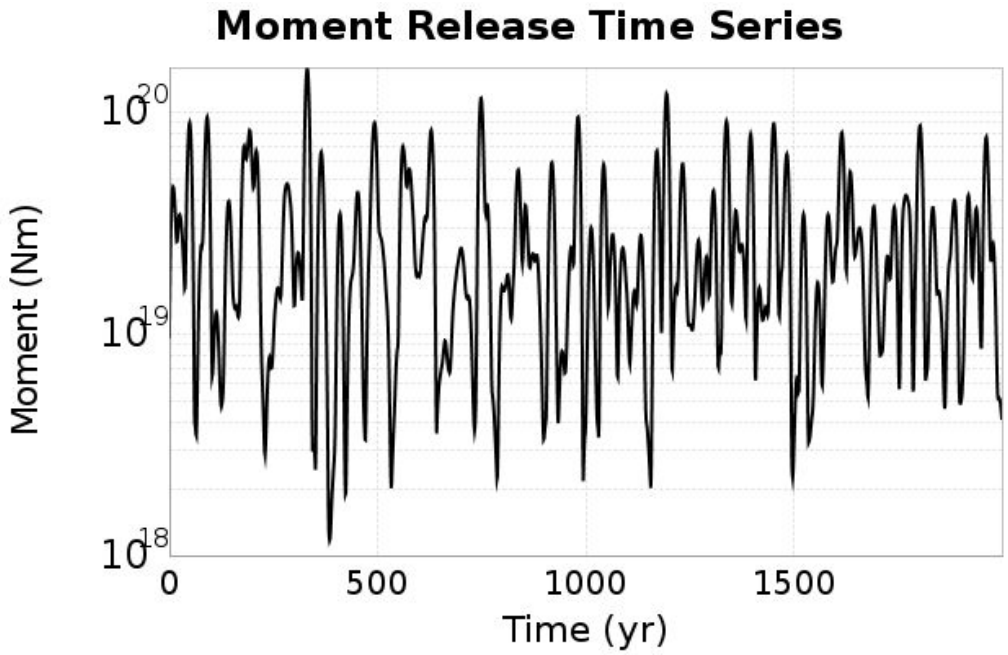
- UCERF3-ETAS question: can larger aftershocks nucleate within the zone of a prior rupture?
  - Field et al. (2015)
  - RSQSim says it's possible, but most likely at the edges of the prior rupture

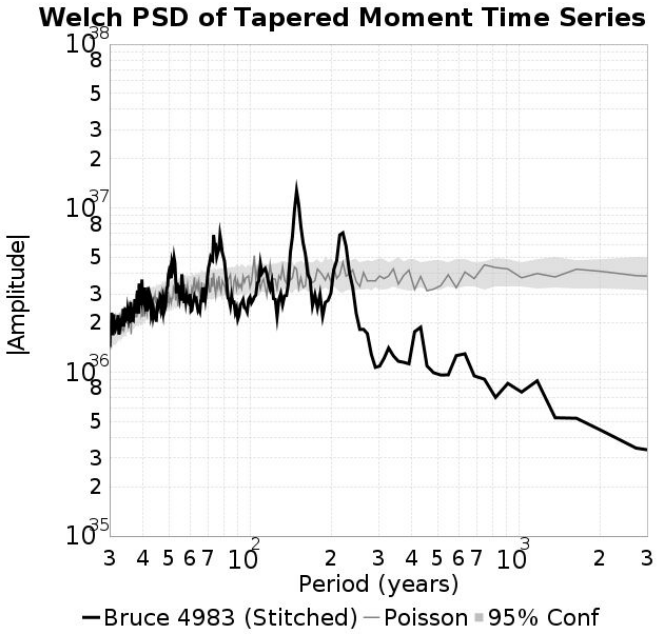


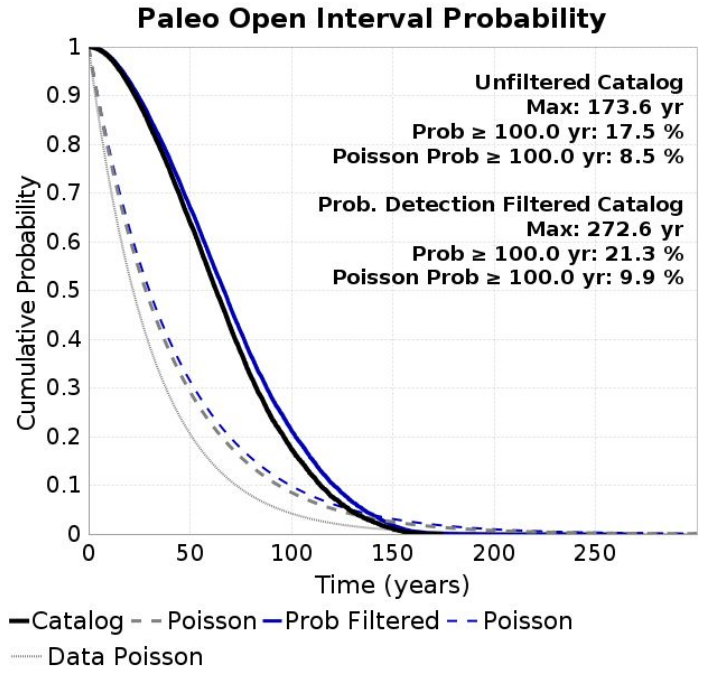


Simulations Are Informing Current Models

- How does moment release vary over time?
- Can supercycles explain the paleoseismic hiatus
  - Biasi and Scharer (2019)

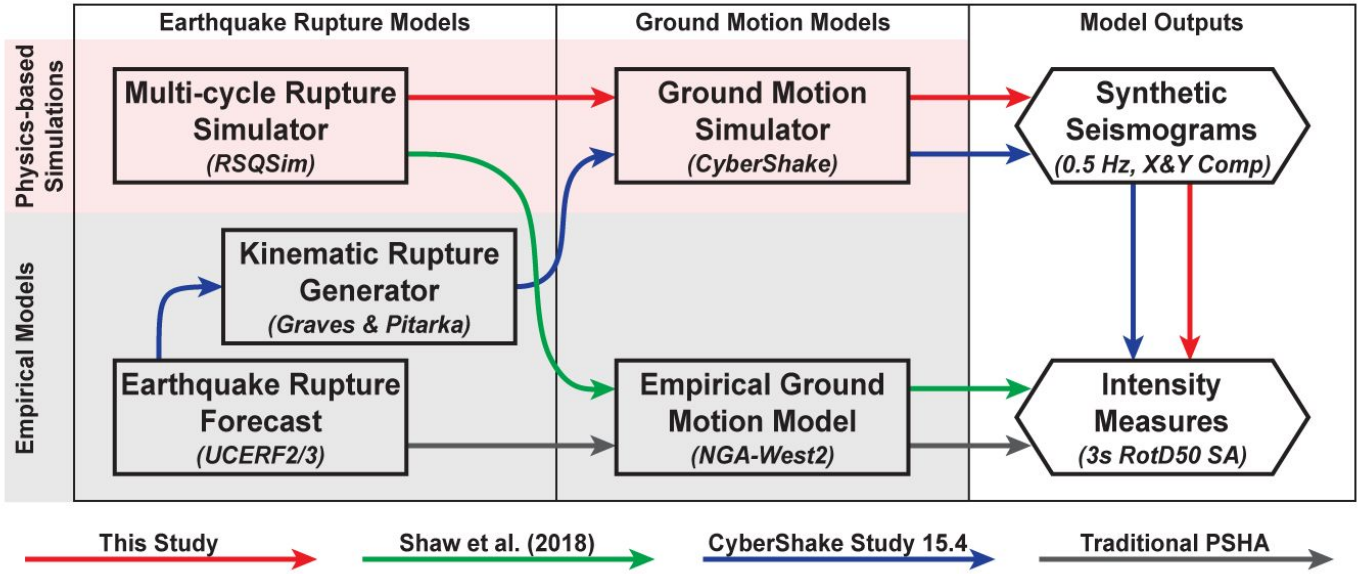






Conclusions

- May pathways currently in use and development for PSHA
- Ultimately, simulation-based may be the best way to reduce uncertainties as models improve
- Alternative models are needed, and will be most useful if they can simulate many seismic cycles on a large and complex fault network



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