10 years of CyberShake: Where are we now and where are we going with physics-based PSHA?

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2017 SCEC Annual Meeting

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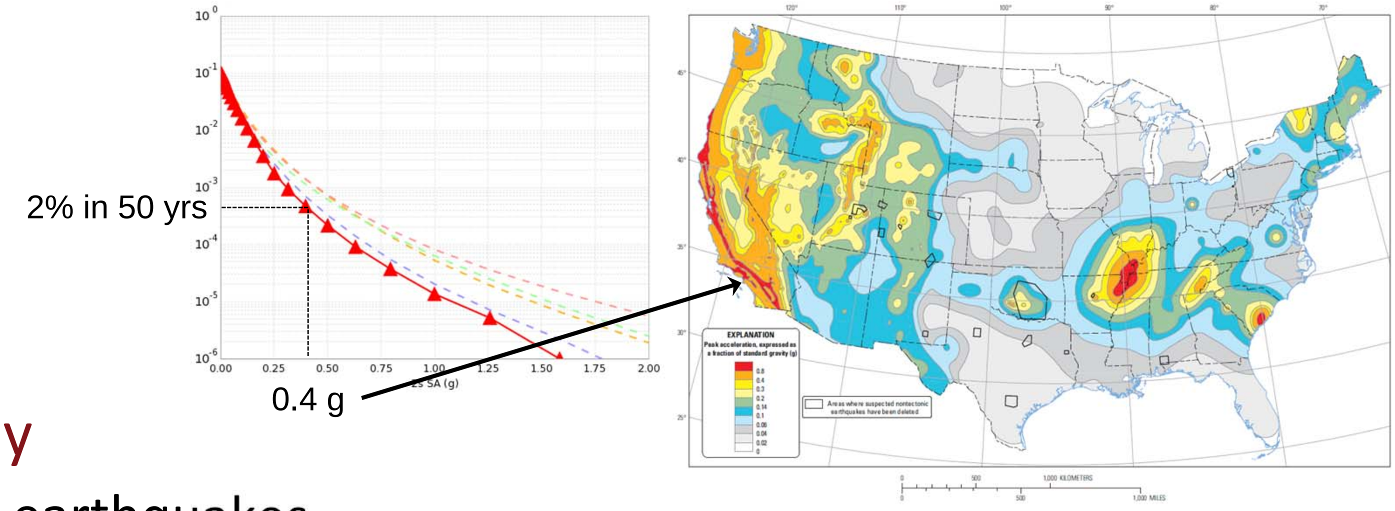
Probabilistic Seismic Hazard Analysis (PSHA)

- Method for probabilistically quantifying expected shaking over a given time frame
- Useful for:
  - Building engineers
  - Disaster planning
  - Insurance rates

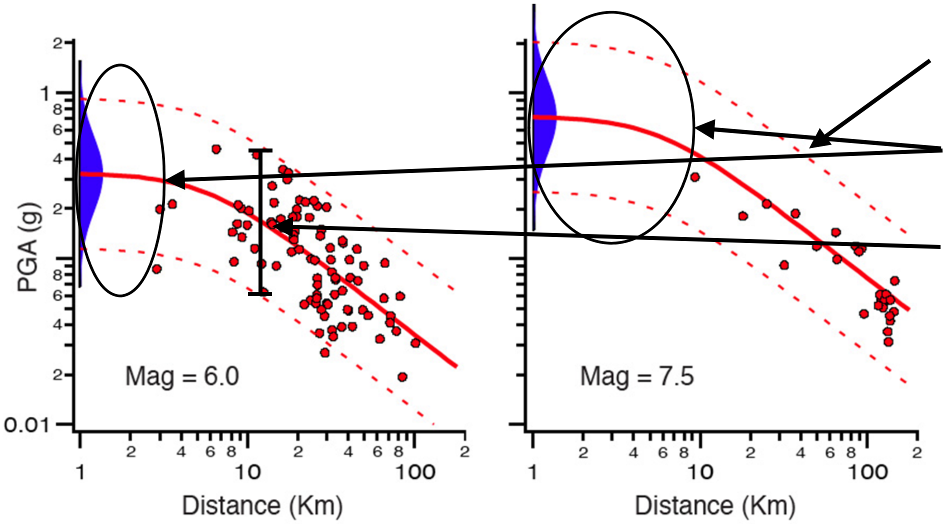


Two-percent probability of exceedance in 50 years map of peak ground acceleration

- PSHA is performed by
  1. Assembling a list of earthquakes
  2. Determining intensity measures from each event
  3. Combining the intensity measures with probability of occurrence

PSHA Approaches

- Empirical – Ground Motion Prediction Equations (GMPEs)

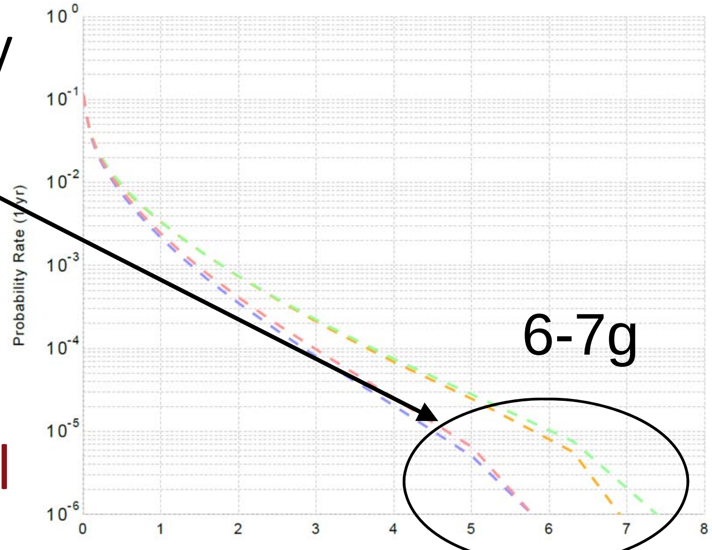


Limited large magnitude data

Limited near-fault data

Large variability

Long tails

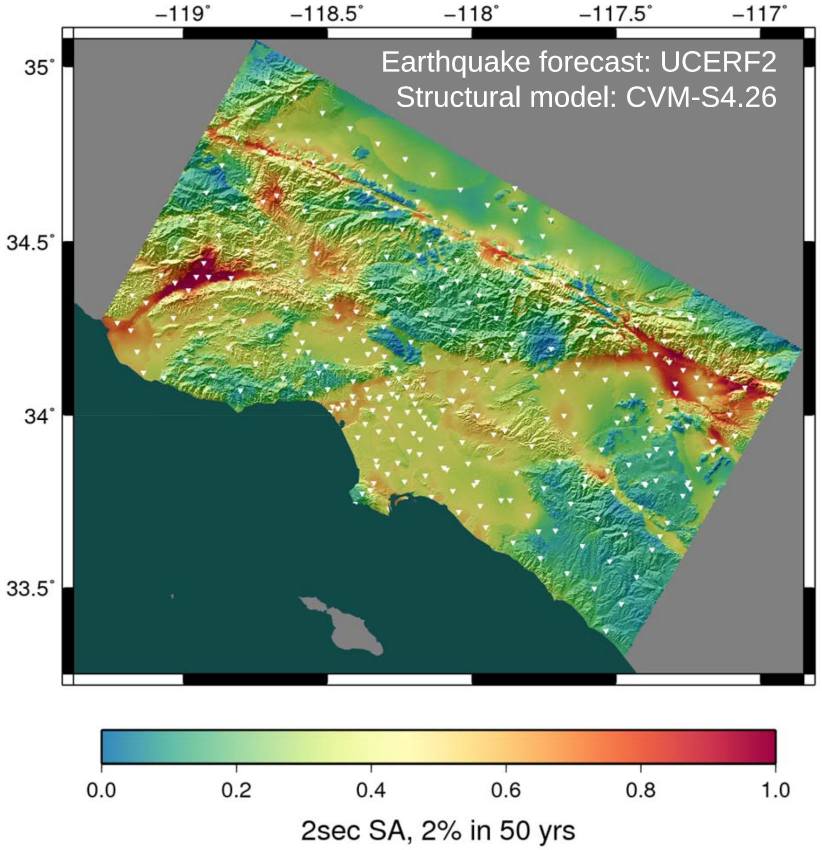


San Bernardino, 1 sec SA (g)

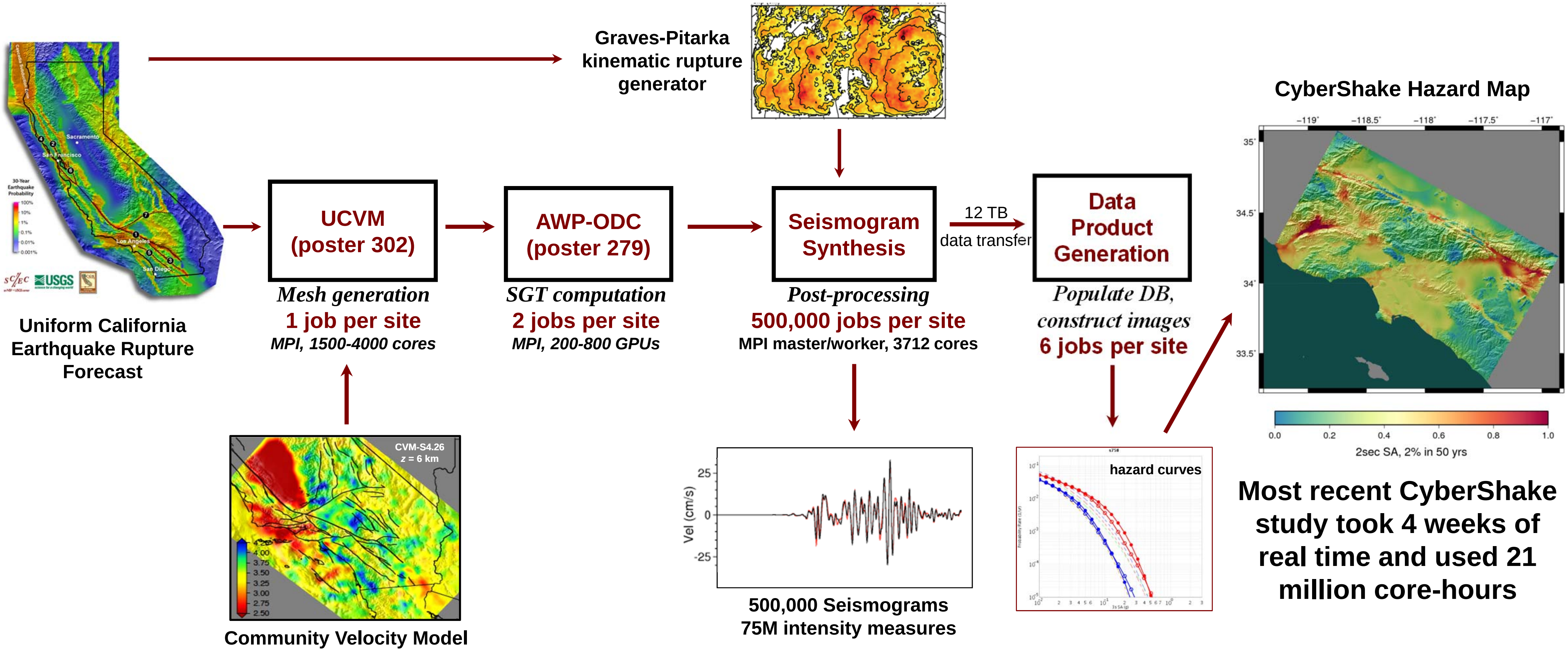
- Simulation – reduce uncertainty by capturing variability in source description, velocity model

What is CyberShake?

- SCEC’s 3D physics-based PSHA platform
- 7,000 ERF ruptures -> 500,000 events
  - Slips and hypocenter locations varied
- Simulating all variations is very expensive
- Instead, use seismic reciprocity
  - 2 simulations per site
  - 200-500 sites needed for map
  - Reduces computation by ~500x
- Interpolate using GMPEs to produce map



CyberShake Data Flow



Uniform California Earthquake Rupture Forecast

Graves-Pitarka kinematic rupture generator

UCVM (poster 302)

Mesh generation

1 job per site

MPI, 1500-4000 cores

Community Velocity Model

AWP-ODC (poster 279)

SGT computation

2 jobs per site

MPI, 200-800 GPUs

Seismogram Synthesis

Post-processing

500,000 jobs per site

MPI master/worker, 3712 cores

500,000 Seismograms
75M intensity measures

12 TB
data transfer

Data Product Generation

Populate DB, construct images

6 jobs per site

CyberShake Hazard Map

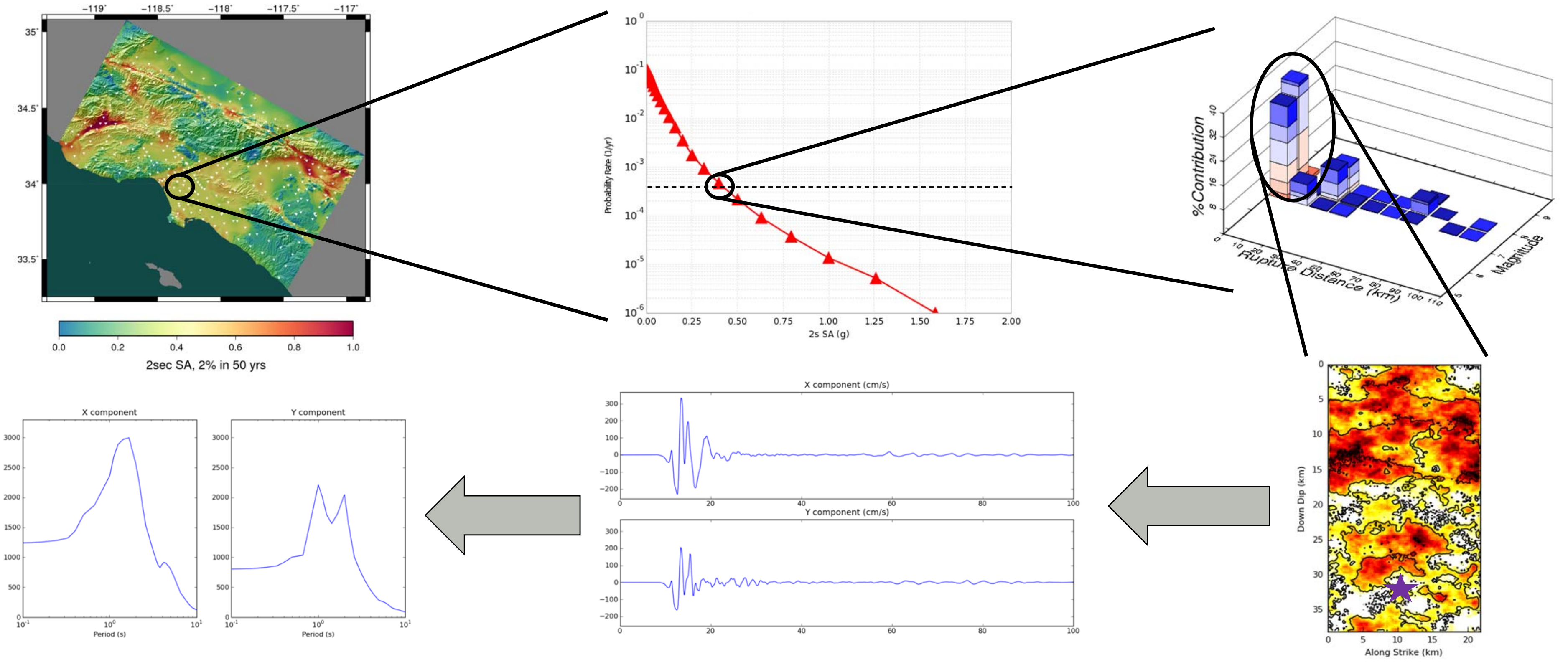
Most recent CyberShake study took 4 weeks of real time and used 21 million core-hours

CyberShake Data Layers

Hazard Map

Hazard Curve

Disaggregation



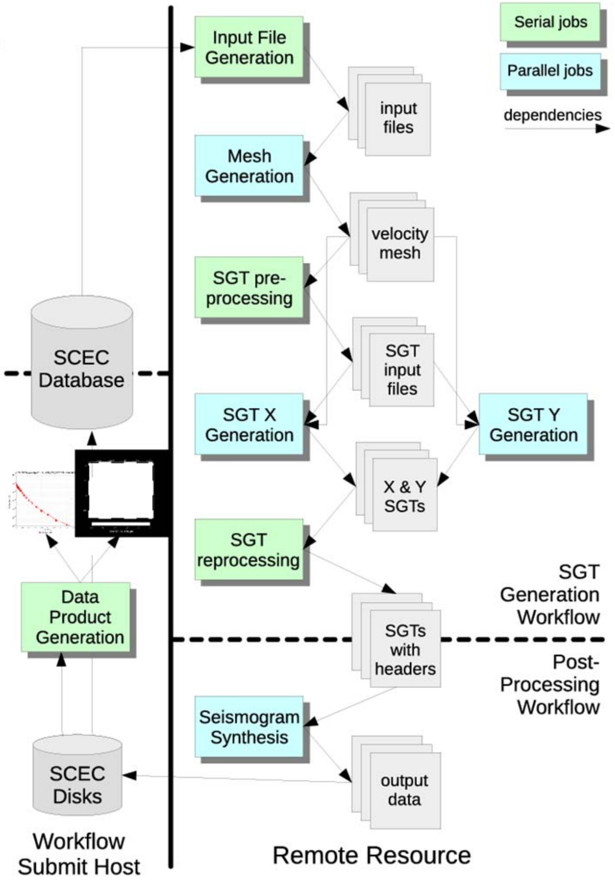
Intensity Measures

Seismograms

Rupture Realization

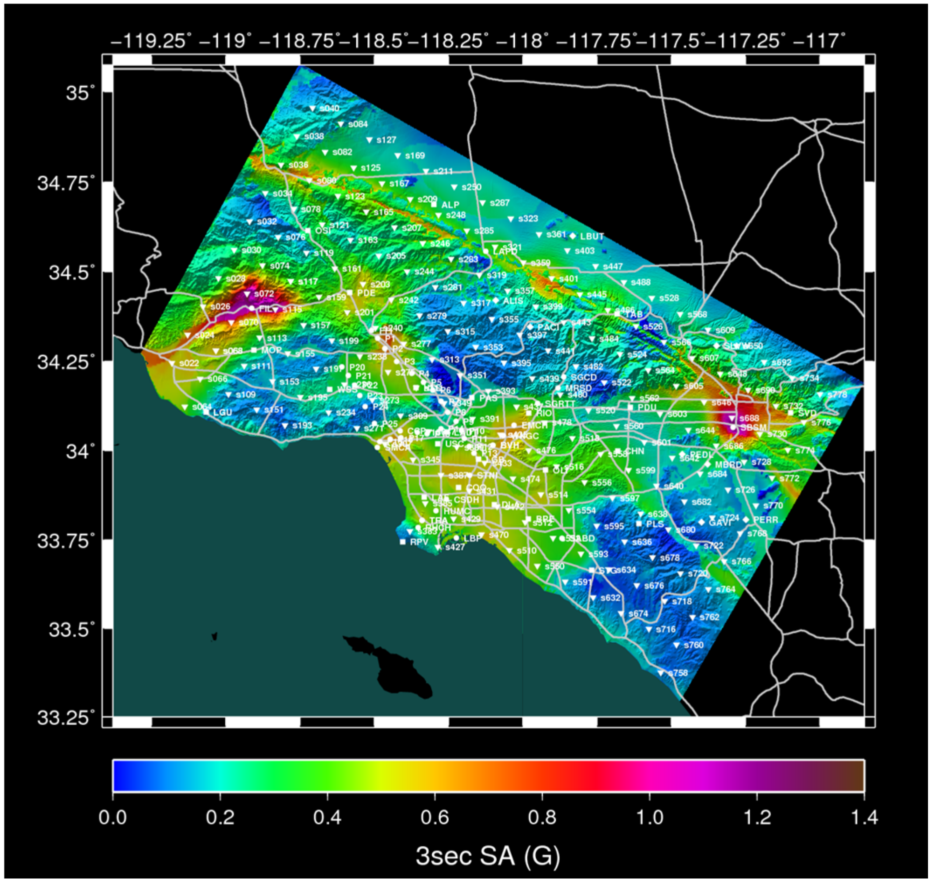
CyberShake Workflows

- Scientific workflow tools orchestrate CyberShake simulations
  - Pegasus-WMS, HTCondor, Globus
  - Create description of workflow with files and dependencies
  - Tools then manage real-time execution of workflow
- Automation: supports running millions of jobs over weeks
- Data management: files are automatically staged in and out
- Resource provisioning: jobs submitted to multiple clusters
- Enabled SCEC to scale CyberShake since 2007
  - 100 million core-hours
  - 2 billion two-component seismograms
  - 210 billion intensity measures



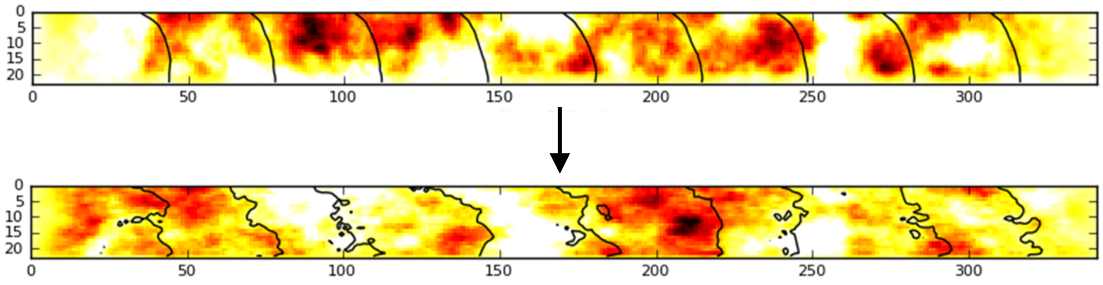
CyberShake Study 1.0

- April-June 2009
- 223 sites in Southern California
- 0.5 Hz
- UCERF 2
- Graves & Pitarka 2007 rupture generator
- Velocity models:
  - CVM-S4

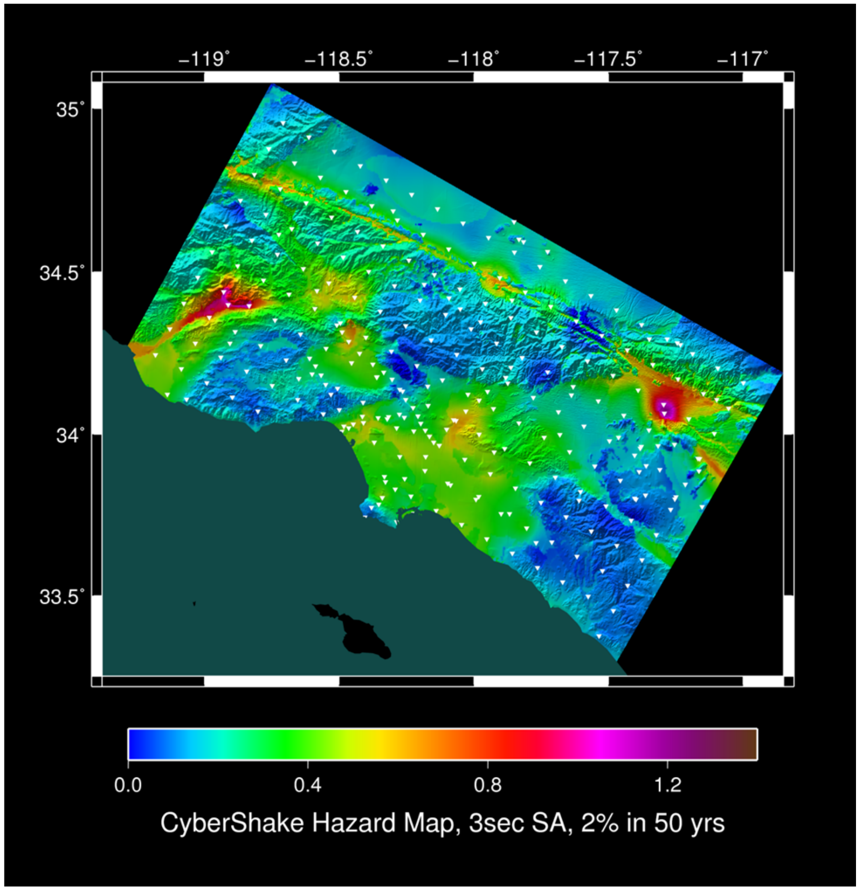


CyberShake Study 2.2

- October 2012 – March 2013
- 223 sites in Southern California
- 0.5 Hz
- UCERF 2
- Graves & Pitarka **2010** rupture generator

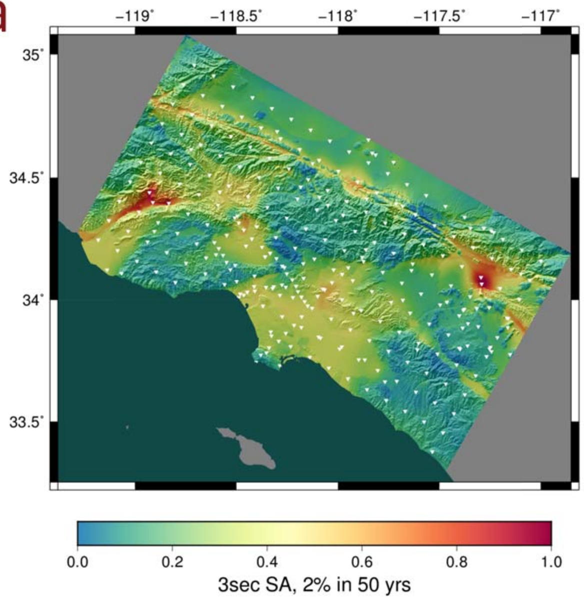


- Velocity models:
  - CVM-S4

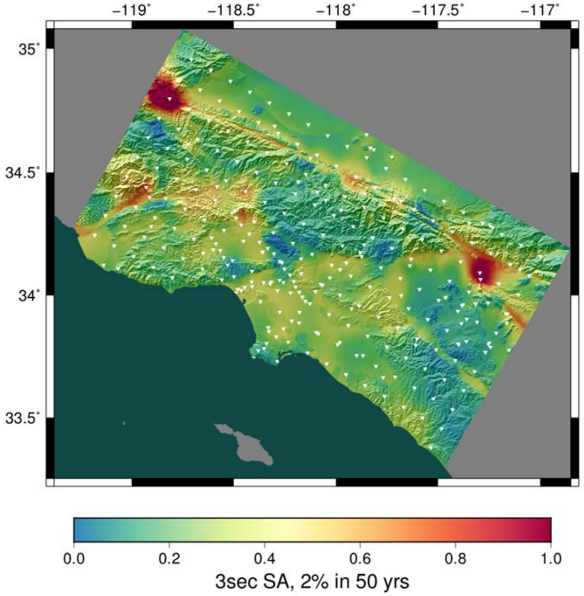


CyberShake Study 13.4

- April – June 2013
- **283** sites in Southern California
- 0.5 Hz
- UCERF 2
- Graves & Pitarka 2010 rupture generator
- Velocity models:
  - CVM-S4
  - **CVM-H**



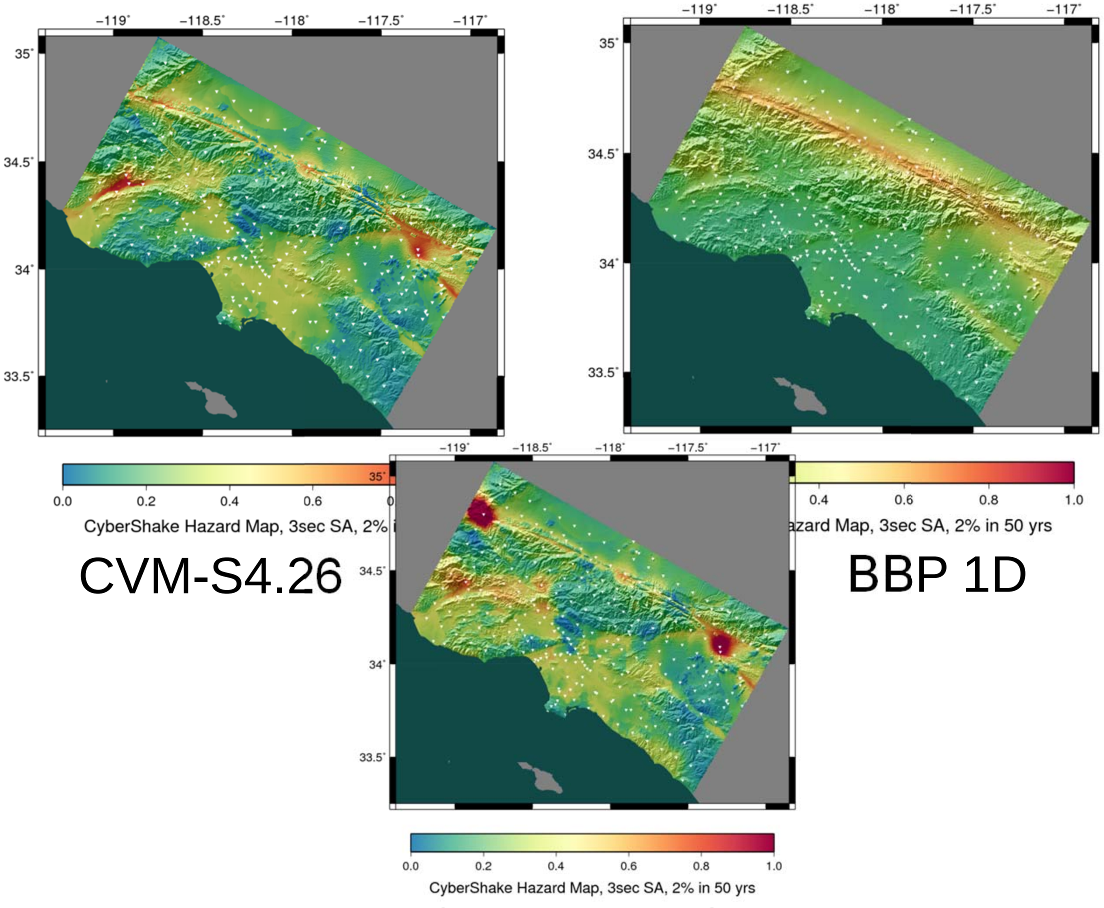
CVM-S4



CVM-H

CyberShake Study 14.2

- February – March 2014
- **286** sites in Southern California
- 0.5 Hz
- UCERF 2
- Graves & Pitarka 2010 rupture generator
- Velocity models:
  - **CVM-S4.26 (tomographic)**
  - **CVM-H, no GTL**
  - **Broadband Platform 1D**



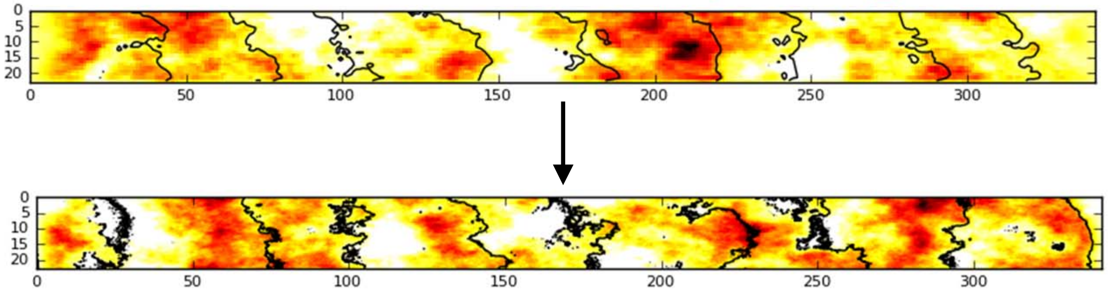
CVM-S4.26

BBP 1D

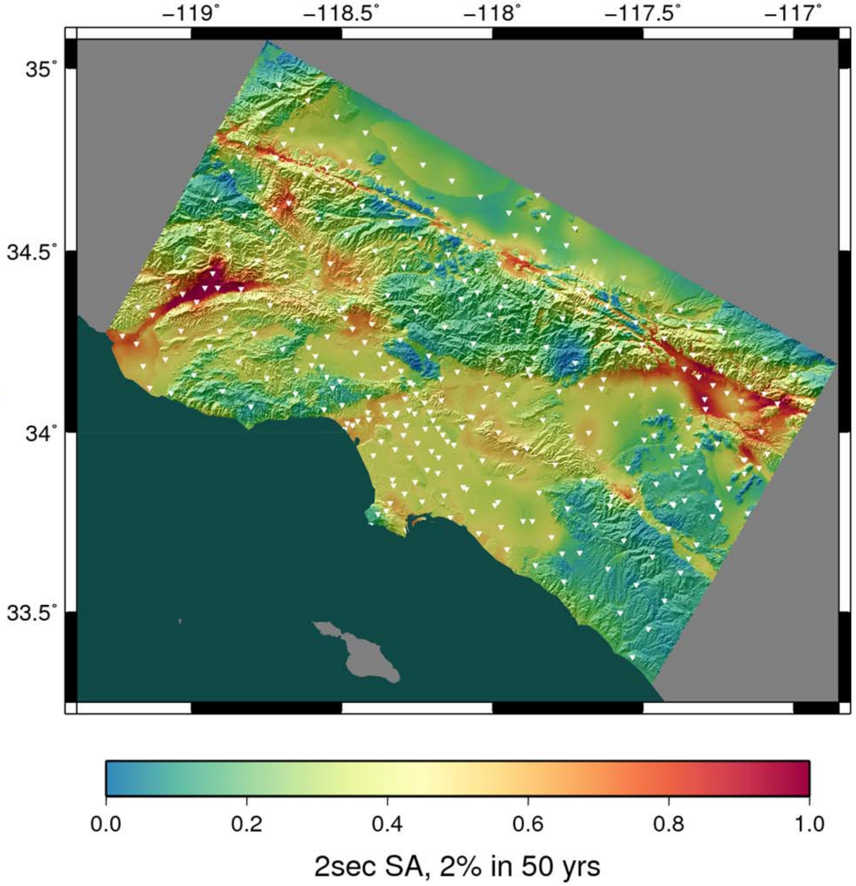
CVM-H, no GTL

CyberShake Study 15.4

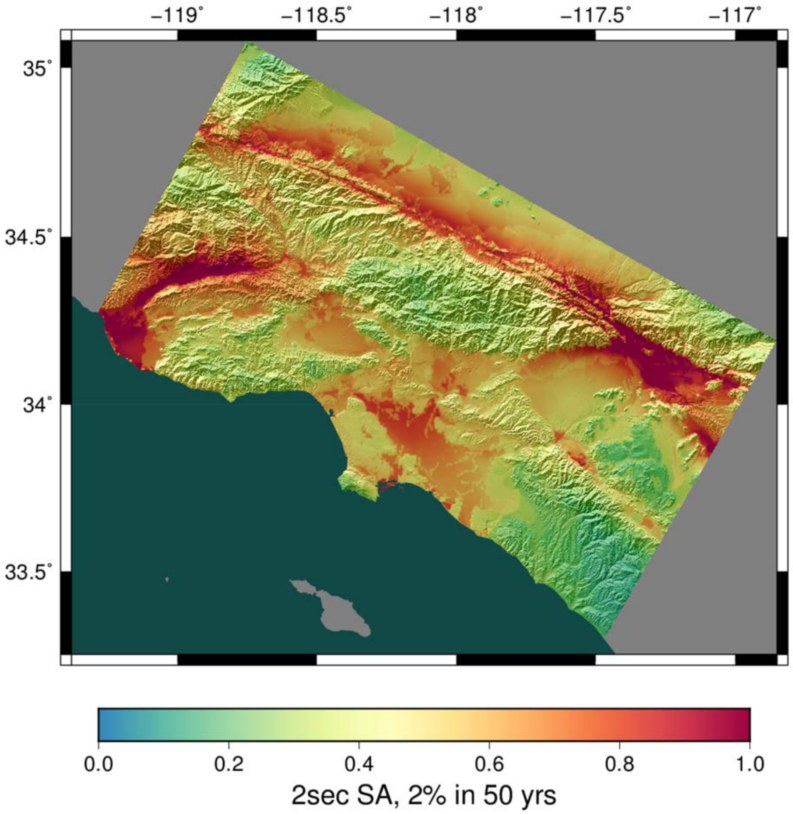
- April – May 2015
- **336** sites in Southern California
- **1.0 Hz**
- UCERF 2
- Graves & Pitarka **2014** rupture generator



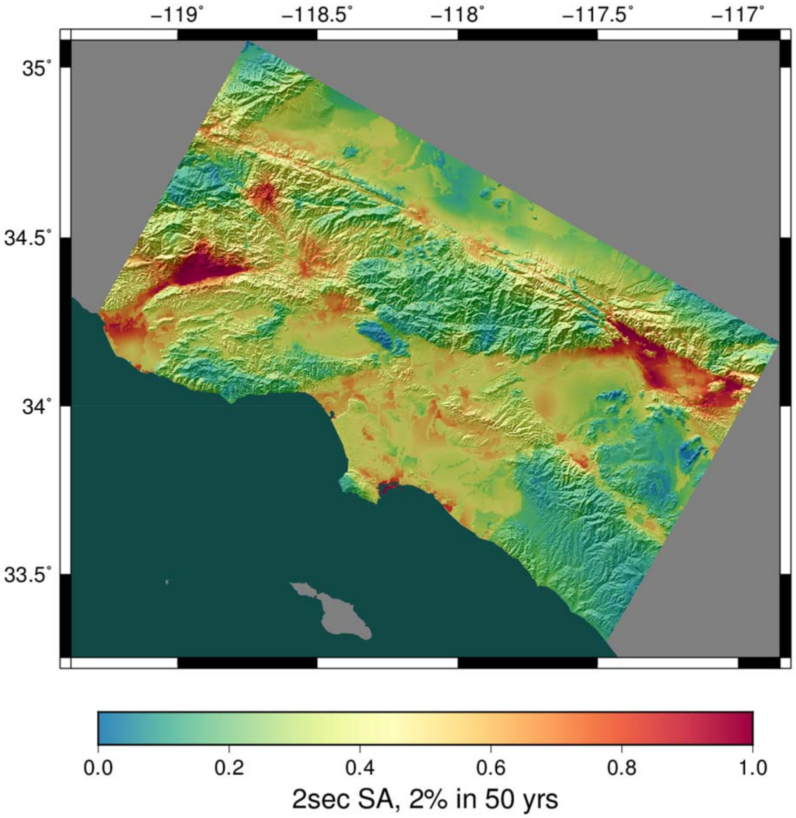
- Velocity models:
  - CVM-S4.26 (tomographic)



CyberShake Study 15.4 comparison with GMPEs



NGA2s



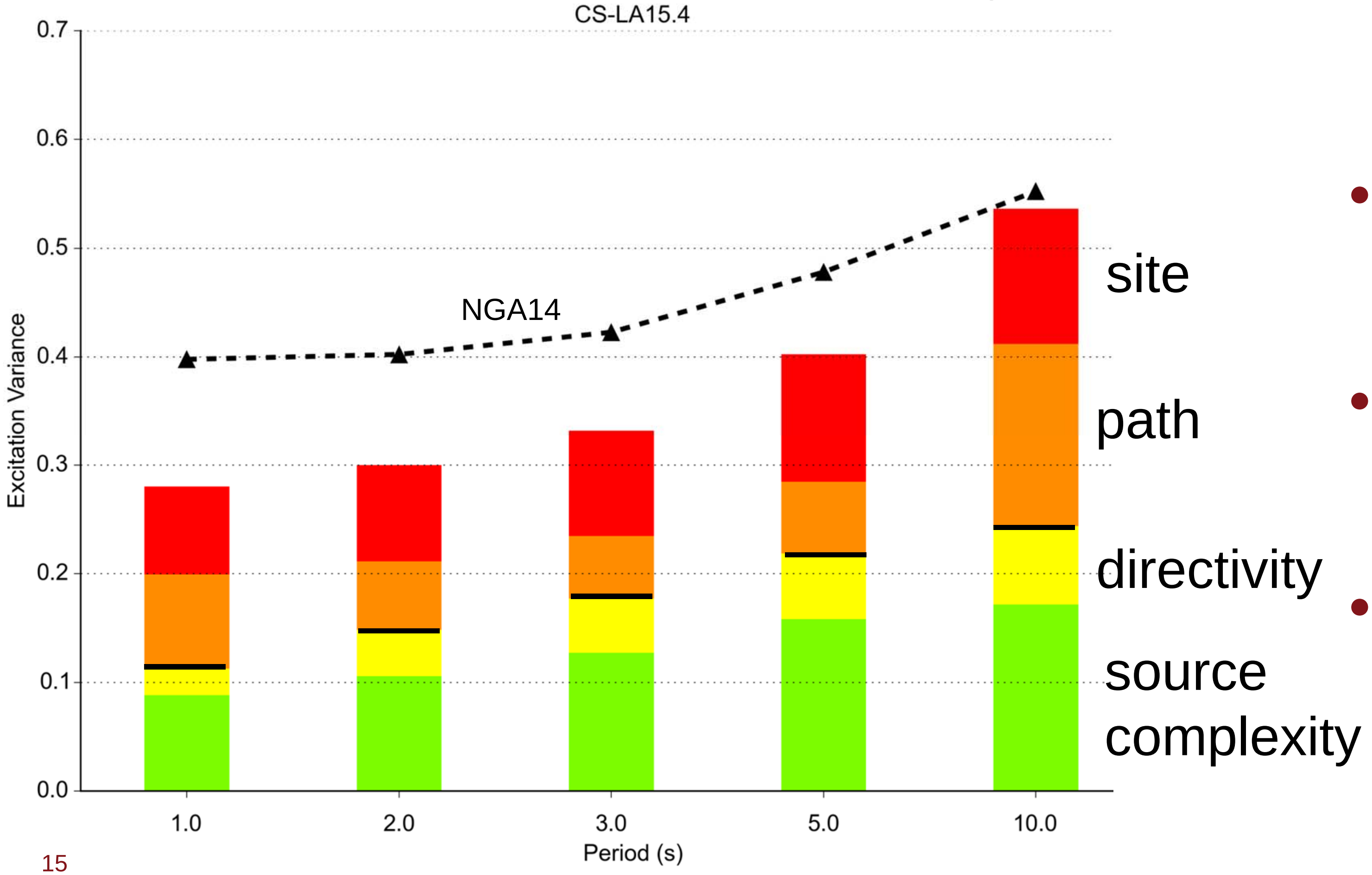
CyberShake Study 15.4

Averaging-Based Factorization (Wang & Jordan, BSSA, 2014)

- GMPEs are easily decomposed into attenuation, site effects, directivity
- To perform similar decomposition for CyberShake, we use ABF
  - Expected shaking intensities are constructed from a hierarchy of sites (*r*), sources (*k*), hypocenters (*x*), and slip variations (*s*)
  - Average over each component and subtract mean to isolate effects
    - Overall level: $A=\left\langle G\left(r,k,x,s\right)\right\rangle_{S,X,K,R}$
    - Site effect: $B(r)=\left\langle G\left(r,k,x,s\right)\right\rangle_{S,X,K}-\left\langle G\left(r,k,x,s\right)\right\rangle_{S,X,K,R}$
    - Path effect: $C(r,k)=\left\langle G(r,k,x,s\right\rangle_{S,X}-\left\langle G(r,k,x,s\right\rangle_{S,X,K}$
    - Directivity effect: $D(r,k,x)=\left\langle G\left(r,k,x,s\right)\right\rangle_{S}-\left\langle G\left(r,k,x,s\right)\right\rangle_{S,X}$
    - Slip complexity effect: $E(r,k,x,s)=G(r,k,x,s)-\left\langle G\left(r,k,x,s\right)\right\rangle_{S}$

$$\underbrace{G(r,k,x,s)}_{\ln(y)} = \underbrace{A}_{\text{Level}}+\underbrace{B(r)}_{\text{Site effect}}+\underbrace{C(r,k)}_{\text{Path effect}}+\underbrace{D(r,k,x)}_{\text{Directivity effect}}+\underbrace{E(r,k,x,s)}_{\text{Slip complexity effect}}$$

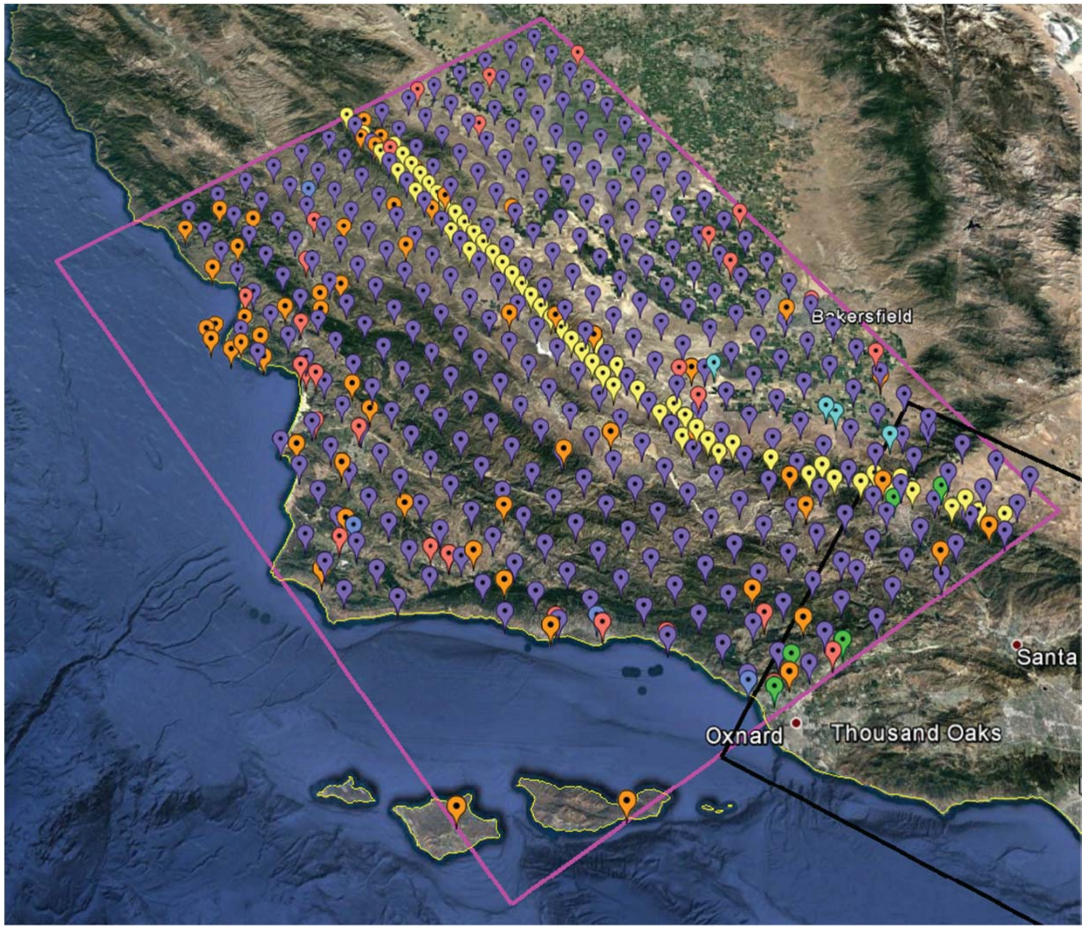
ABF comparisons



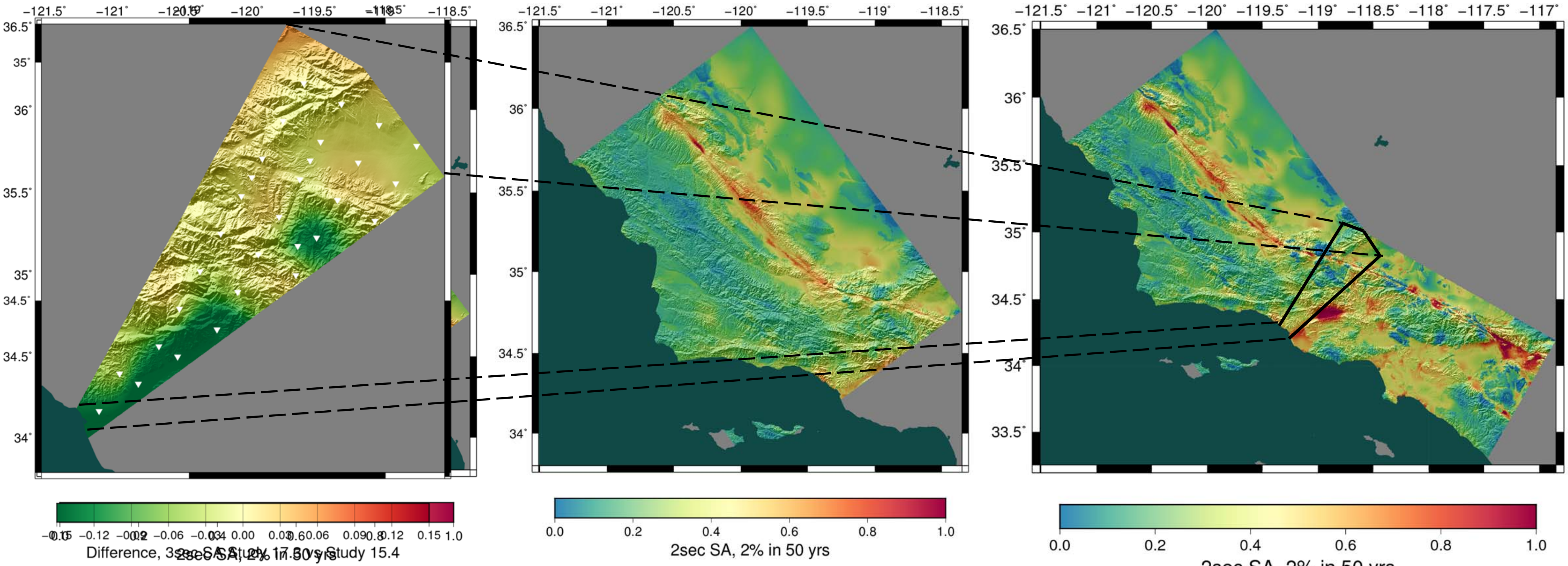
- ABF terms are uncorrelated, enabling breakdown of variance
- Physics-based PSHA has the potential to reduce site and path variance
- Could reduce long tails

Study 17.3 overview

- March – April 2017
- 438 sites in **Central** California
- 1.0 Hz
- UCERF 2
- Graves & Pitarka 2014 rupture generator
- Velocity models:
    - **CCA-06 (3D tomographic)**
    - **CCA 1D**
    - **Tiled models with smoothing**



Study 17.3 results (poster 303)



Difference, Study 17.3 – Study 15.4

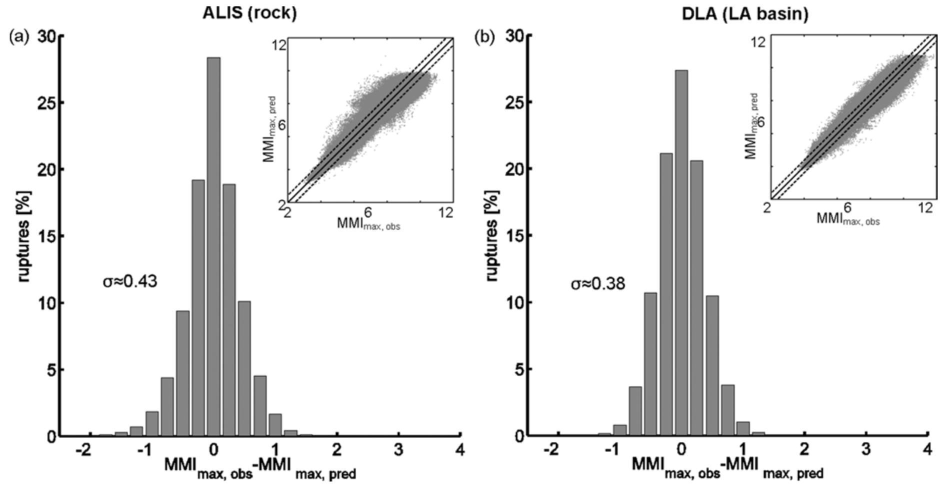
CCA 1D

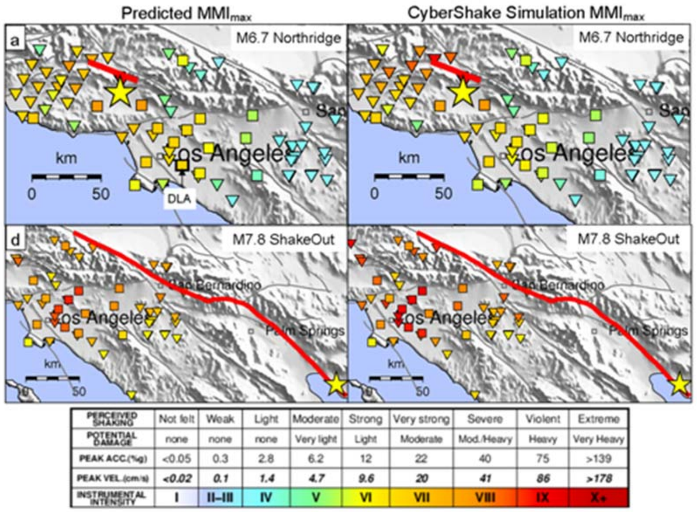
CCA-06 (3D)

Combined 3D

CyberShake and Earthquake Early Warning

- CyberShake provides large dataset of simulated M6.5+ events
- Used to train model to predict MMI_{max} (Böse et al., Geophys. J. Int., 2014)
- CyberShake was augmented with stochastic high-frequency data, using the Graves & Pitarka method

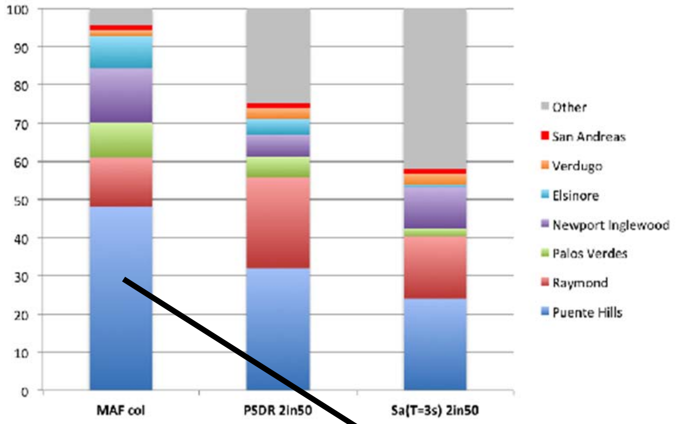


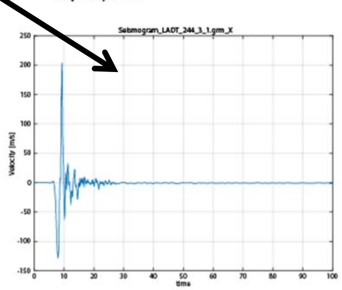


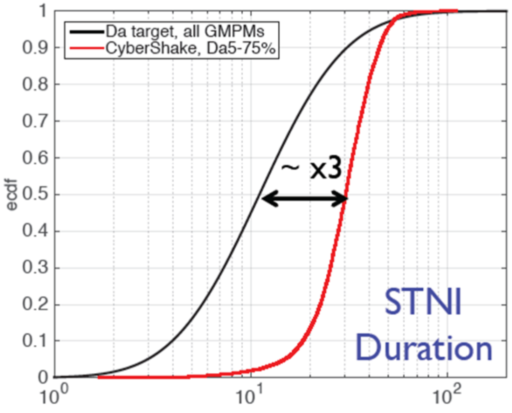
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

CyberShake for Building Engineering Applications

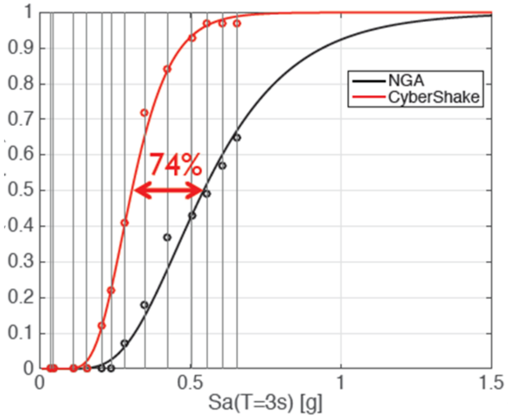
- Deierlein et al., 2016 SCEC Meeting
- CyberShake (+ stochastic) intensity measures and durations used to examine building response at high intensities
- Can disaggregate to examine seismograms



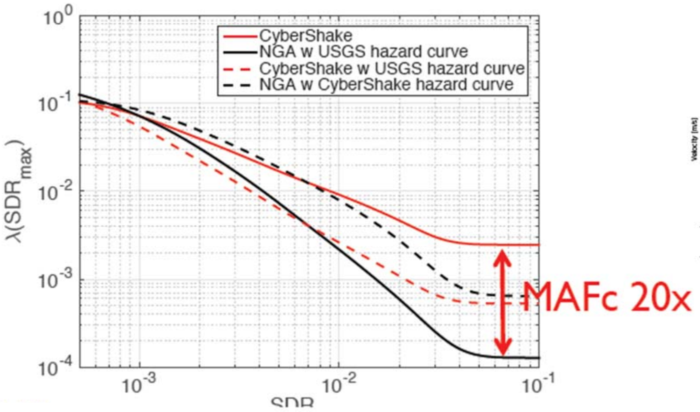




Significant Duration, Ds (s)



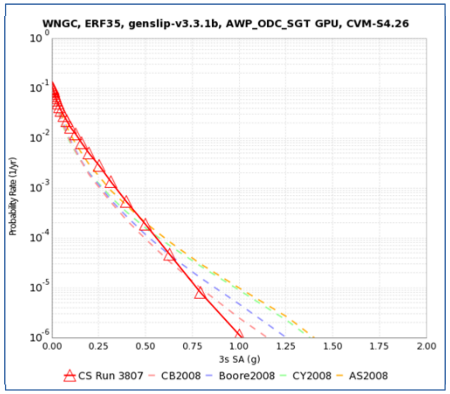
Collapse Fragility



Story Drift Exceedence

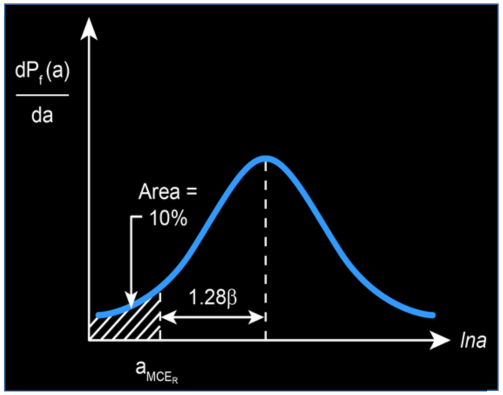
SCEC Utilization of Ground Motion Simulation Committee

- CyberShake results are being considered as inputs to seismic codes under Project 17
- Hazard curves convolved with fragility function to produce MCE_R
- CyberShake MCE_R results are combined with GMPEs in a period-dependent way to produce overall results



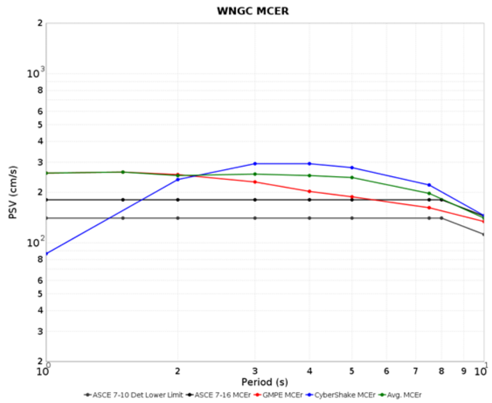
CyberShake Hazard Curve

+



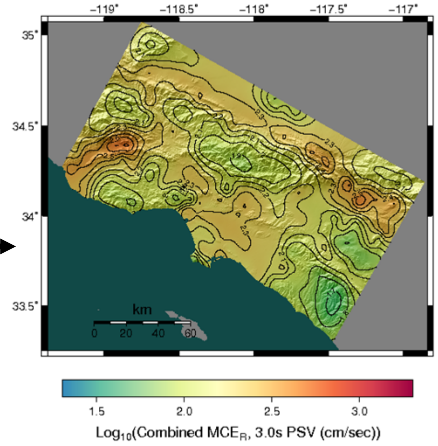
Fragility Function

→



MCE_R for 1 site

→



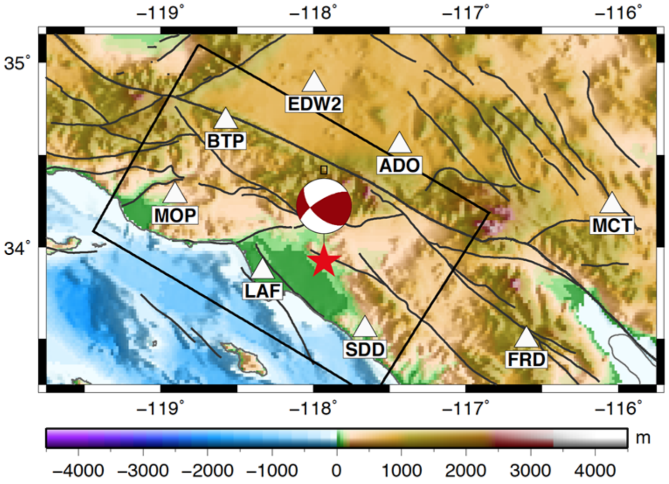
MCE_R for region

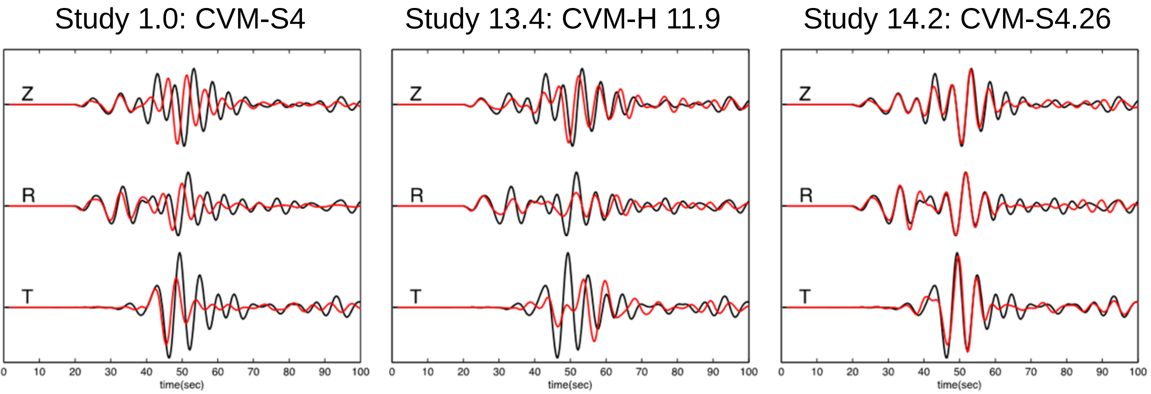
CyberShake Validation

03/28/14 La Habra Earthquake (M5.1)

Station EDW2
Observed in black
Synthetic in red

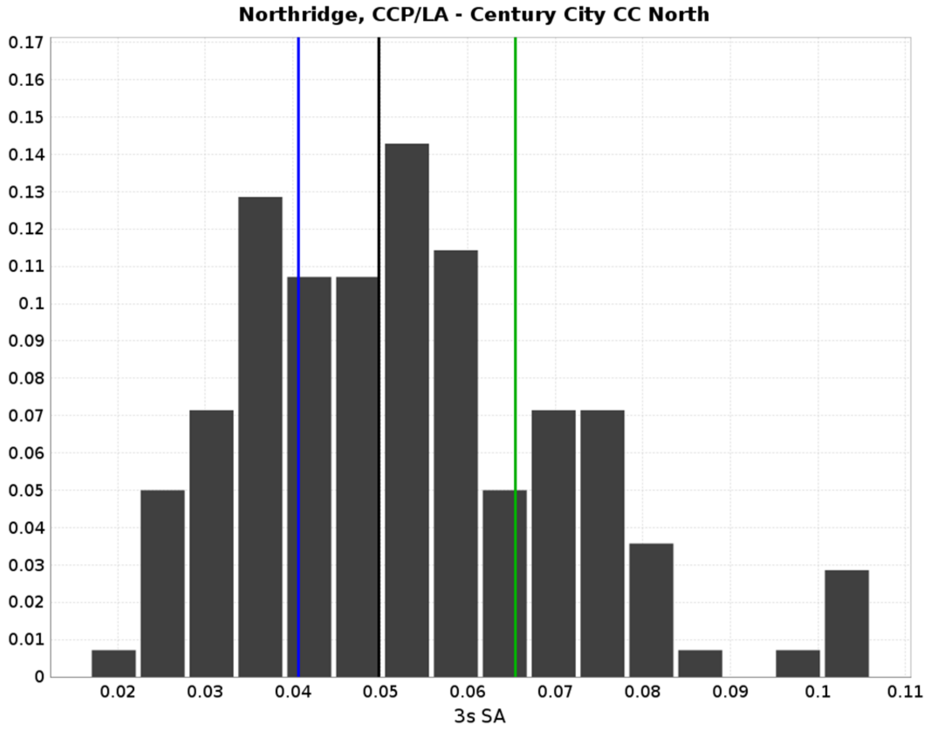
Lee, Chen & Jordan (2014)




Study 1.0: CVM-S4

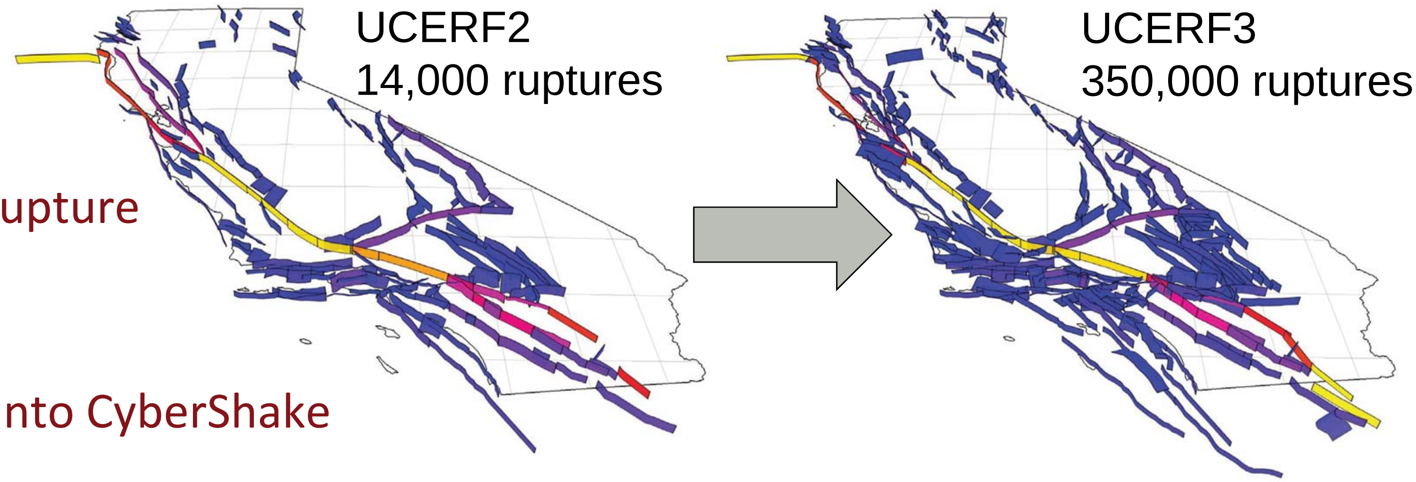
Study 13.4: CVM-H 11.9

Study 14.2: CVM-S4.26



Histogram of CyberShake amplitudes
Green: Northridge recording
Blue: GMPE log-mean
Black: CyberShake log-mean

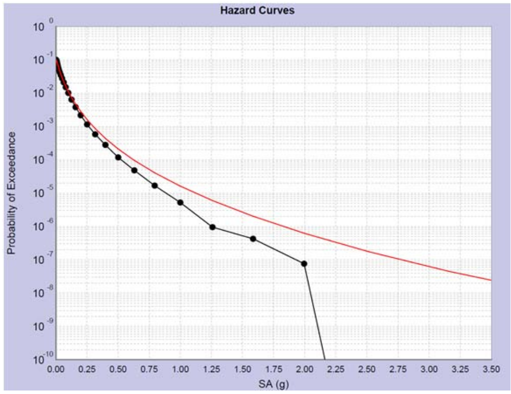
Future directions

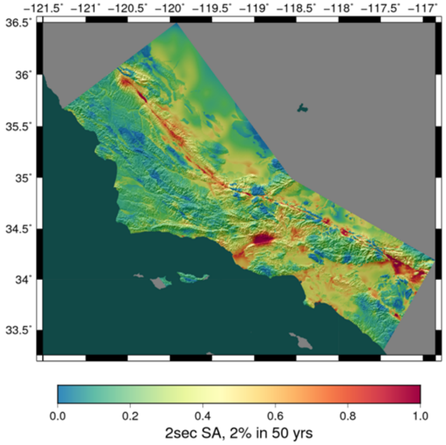


- Move to new ERF
  - UCERF 3
    - Must reduce size of rupture set to be tractable
  - RSQSim
    - Feed events directly into CyberShake
- Increase maximum frequency
- Add new physics: Q(*f*), velocity model heterogeneities, non-linear effects
- Continue to run CyberShake in new regions
  - San Diego? Bay Area?

Conclusion

- CyberShake provides an alternative approach for calculating PSHA
- Integrates current models and software from other SCEC efforts
- Provides promise of reducing hazard uncertainties
- Rich suite of CyberShake data products is useful for many applications





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2007

2017

2027

Thanks!

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