High-Frequency, Physics-Based Simulations for Earthquake System Science

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Y. Cui [2], **K. Olsen** [3], **R. Taborda** [4], **J. Bielak** [5], **P. Small** [1], **E. Poyraz** [2], **J. Zhou** [2], **P. Chen** [6], **E.-J. Lee** [1], **S. Callaghan** [1], **R. Graves** [7], **P. J. Maechling** [1], **D. Gill** [1], **K. Milner** [1], **F. Silva** [1], **S. Day** [3], **K. Withers** [3], **W. Savran** [3], **Z. Shi** [3], **M. Norman** [8], **H. Finkel** [9], **G. Juve** [10], **K. Vahi** [10], **E. Deelman** [10], **H. Karaoglu** [5], **Y. Isbiliroglu** [11], **D. Restrepo** [12], **L. Ramirez-Guzman** [13]

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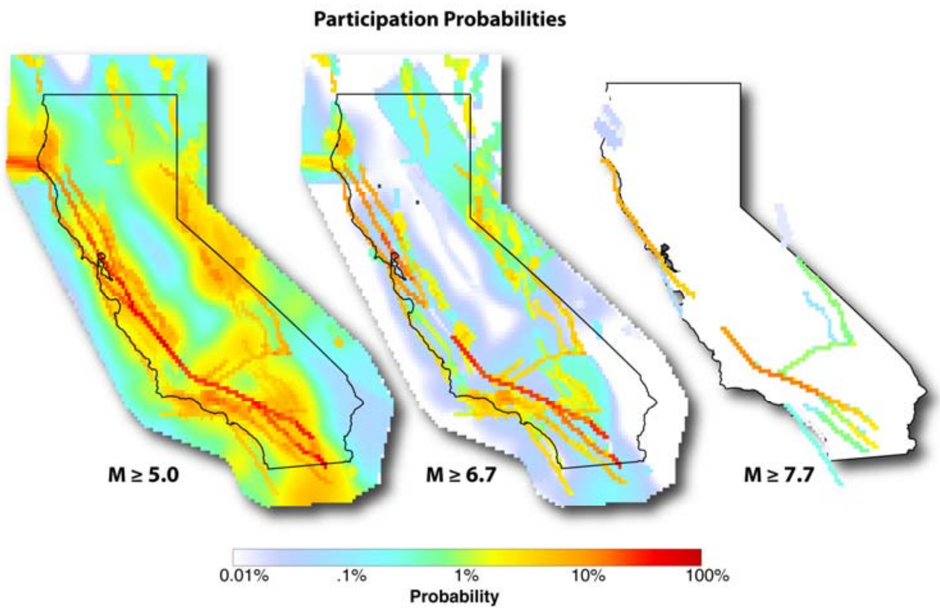
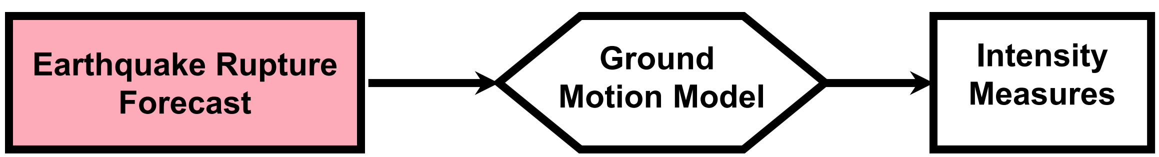
OLCF Symposium, 22 July 2014

Probabilistic Seismic Hazard Model



SCEC-USGS-CGS Working Group on California Earthquake Probabilities (2008)

Uniform California Earthquake Rupture Forecast (UCERF2)

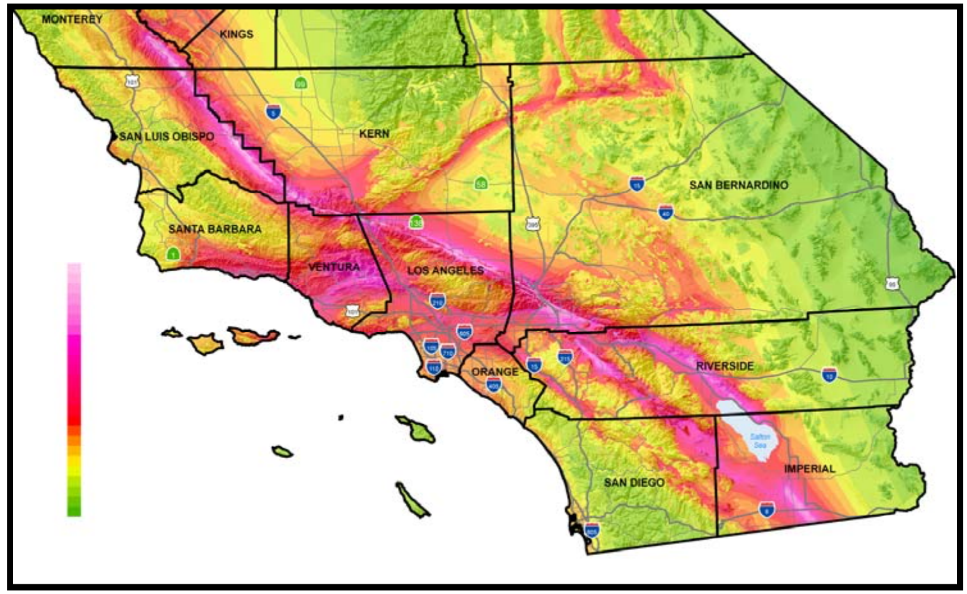


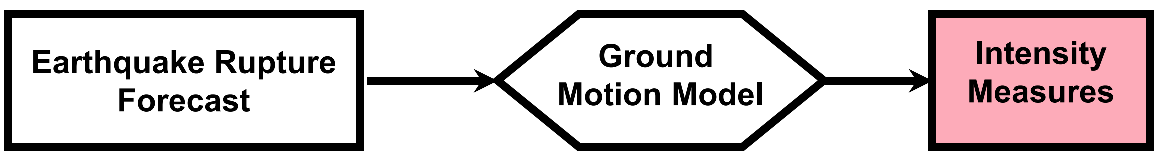
$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Probabilistic Seismic Hazard Model

National Seismic Hazard Map

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





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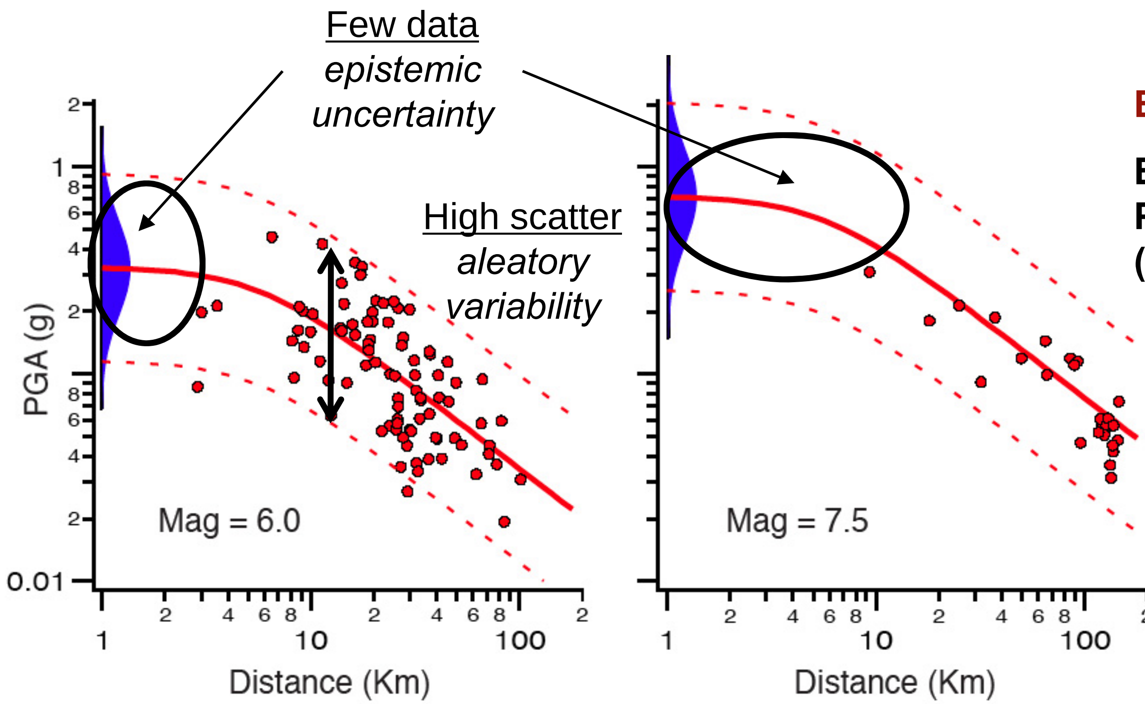
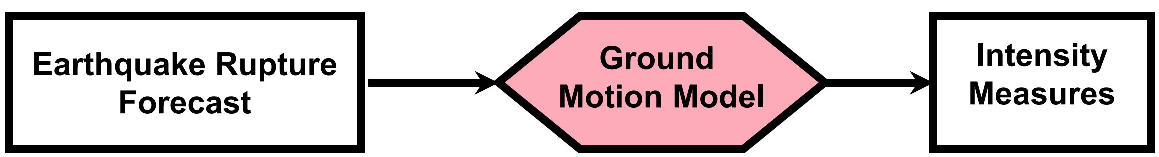
Probabilistic Seismic Hazard Model



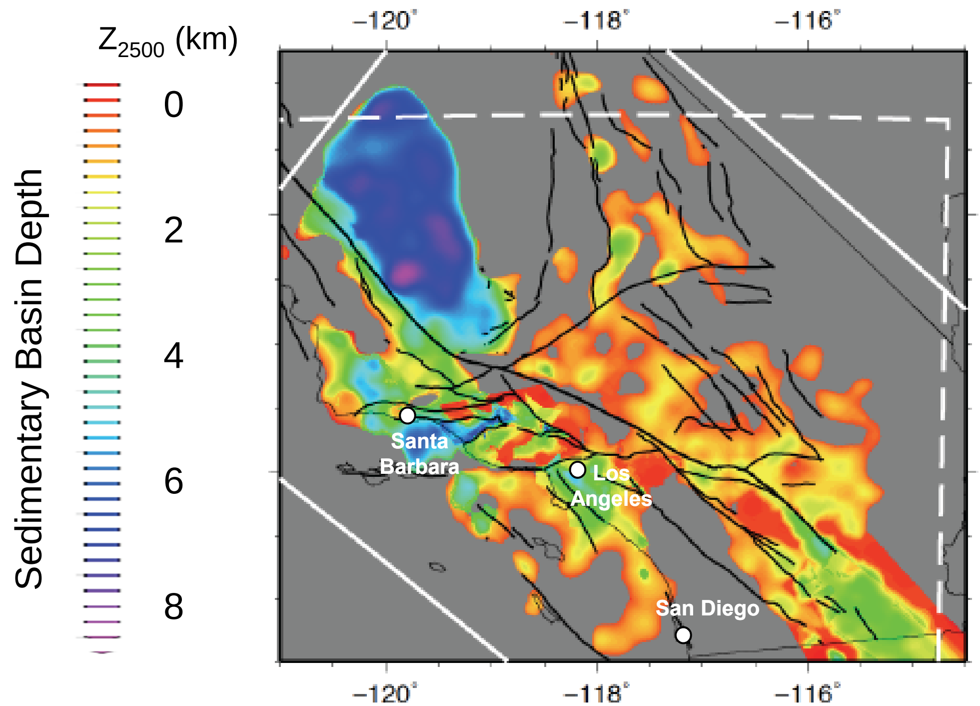
Boore et al. (1997)

Empirical Ground Motion Prediction Equations (GMPEs)



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

Probabilistic Seismic Hazard Model

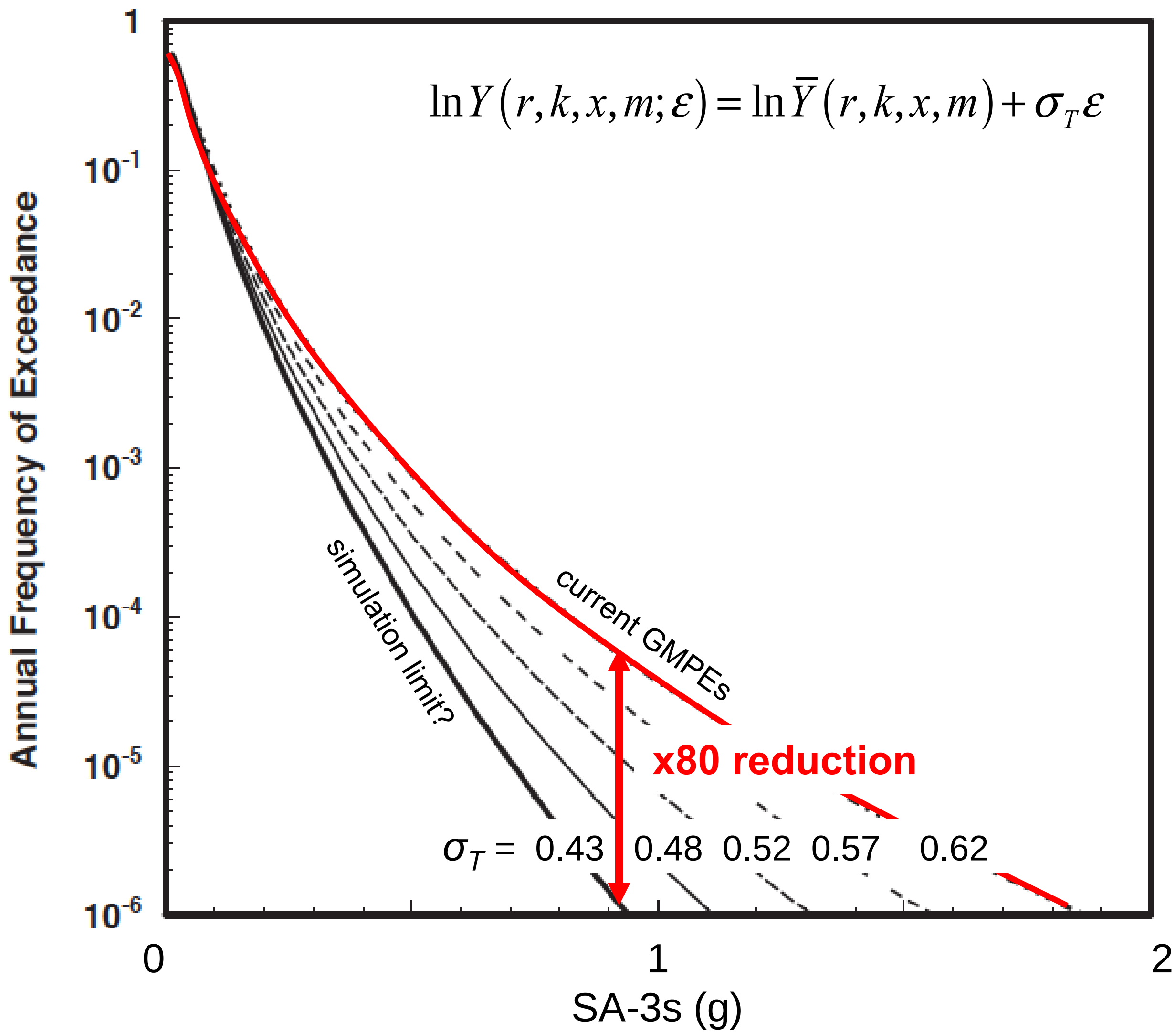


Much of the aleatory variability in the GMPEs comes from 3D heterogeneity in crustal structure

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

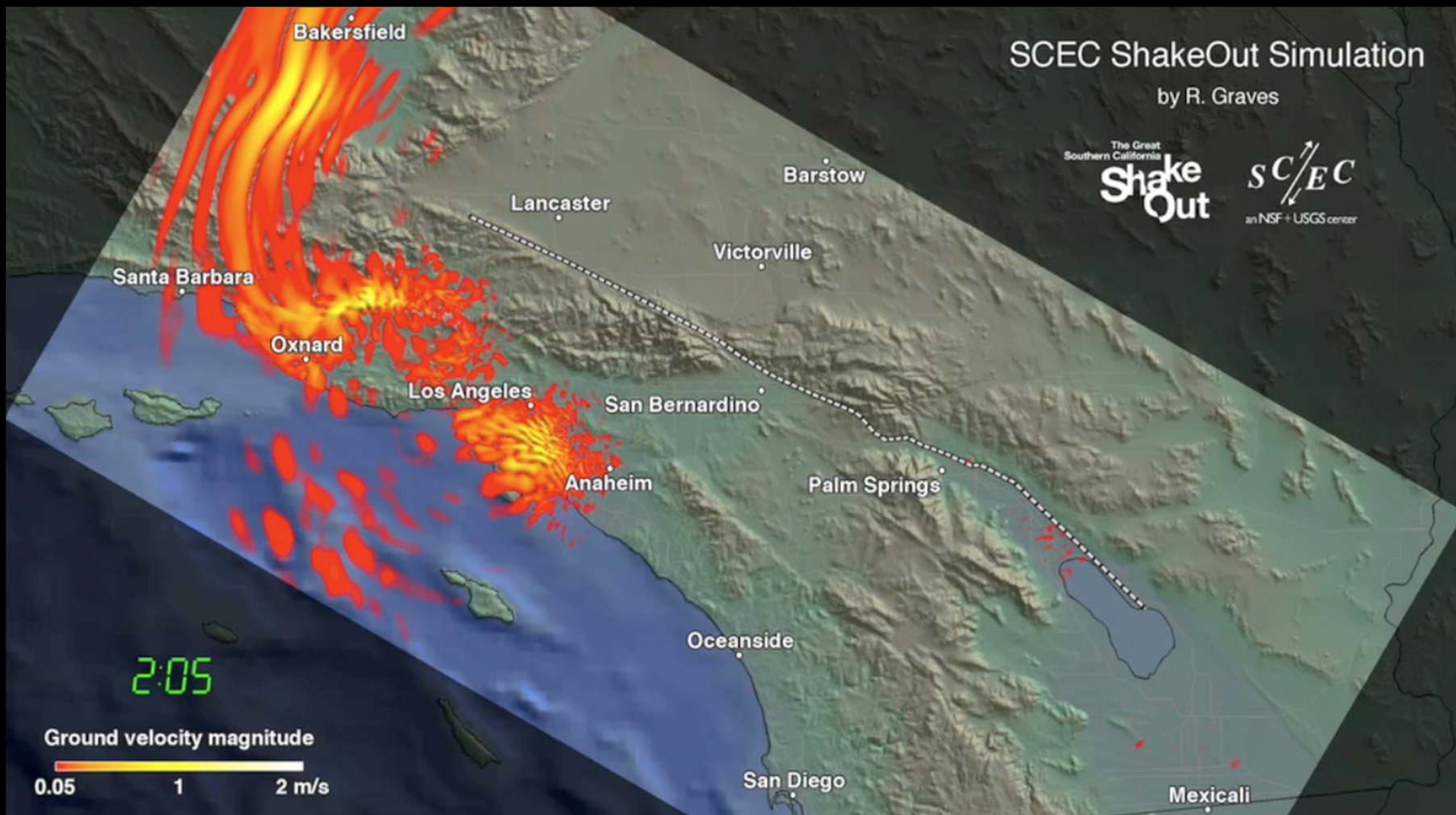
$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Importance of Reducing Aleatory Variability

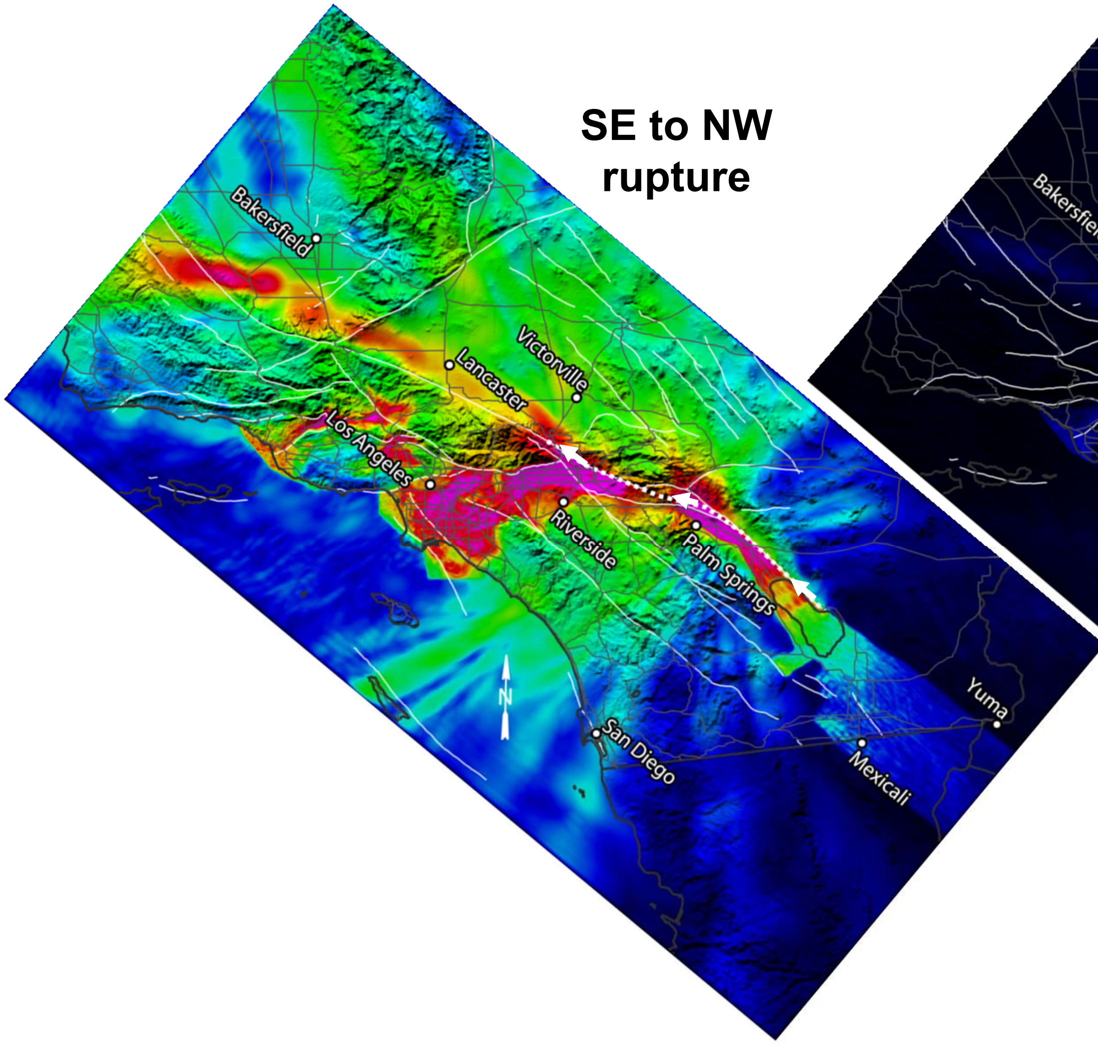


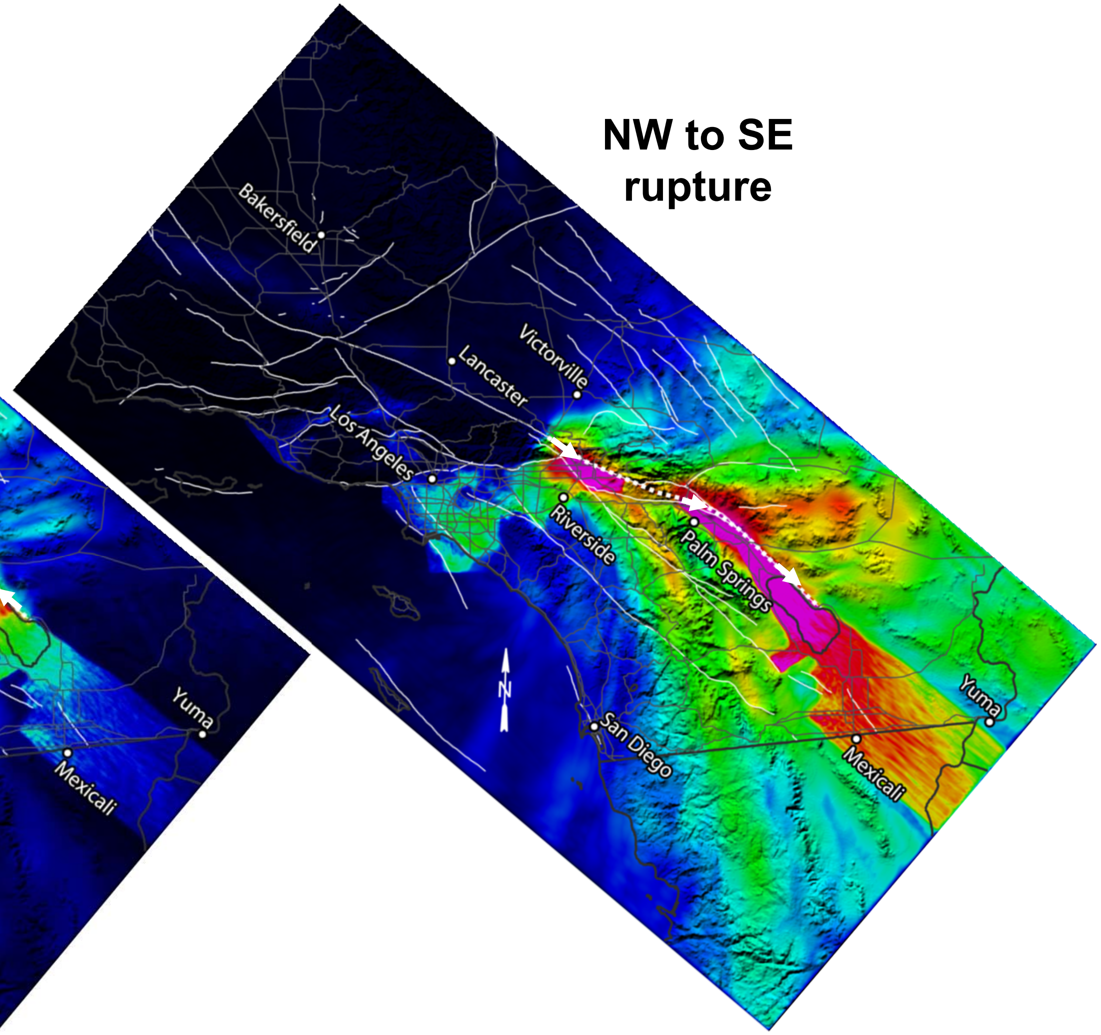
ShakeOut Scenario

M7.8 Earthquake on Southern San Andreas Fault



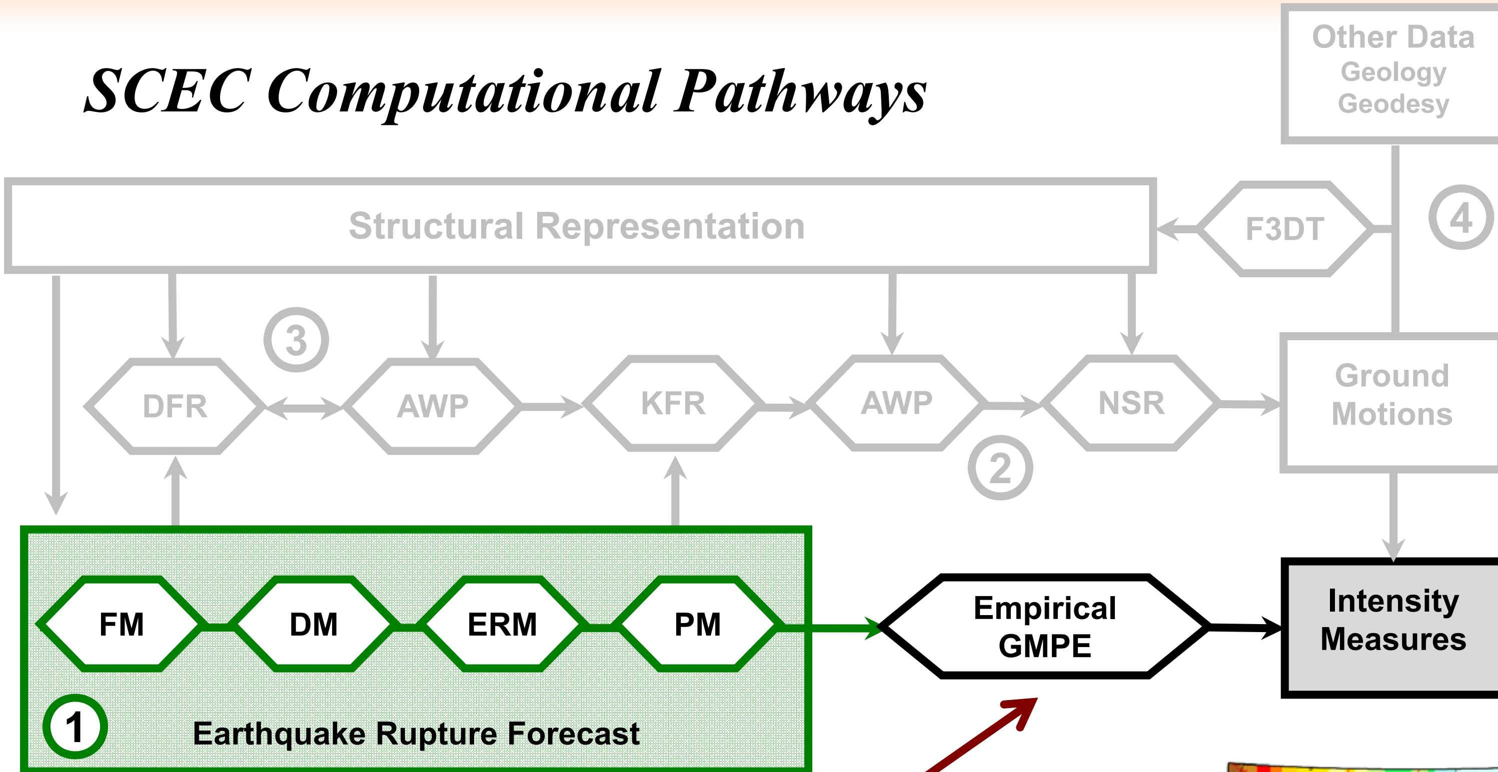
Coupling of Directivity and Basin Effects



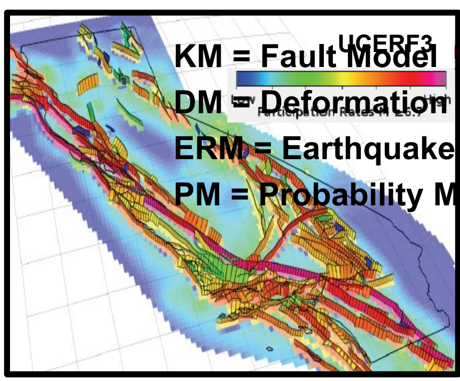


TeraShake simulations of M7.7 earthquake on Southernmost San Andreas

SCEC Computational Pathways



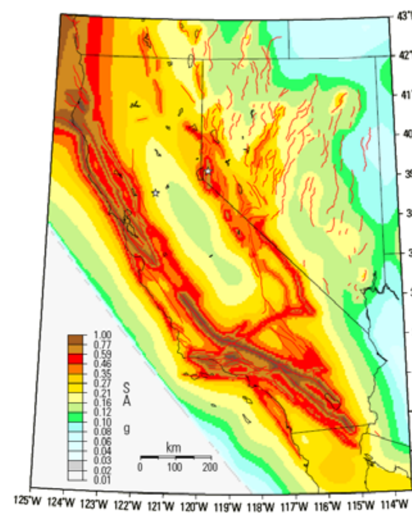
TACC *Stampede*



KM = Fault Model
DM = Deformation Model
ERM = Earthquake Rate Model
PM = Probability Model

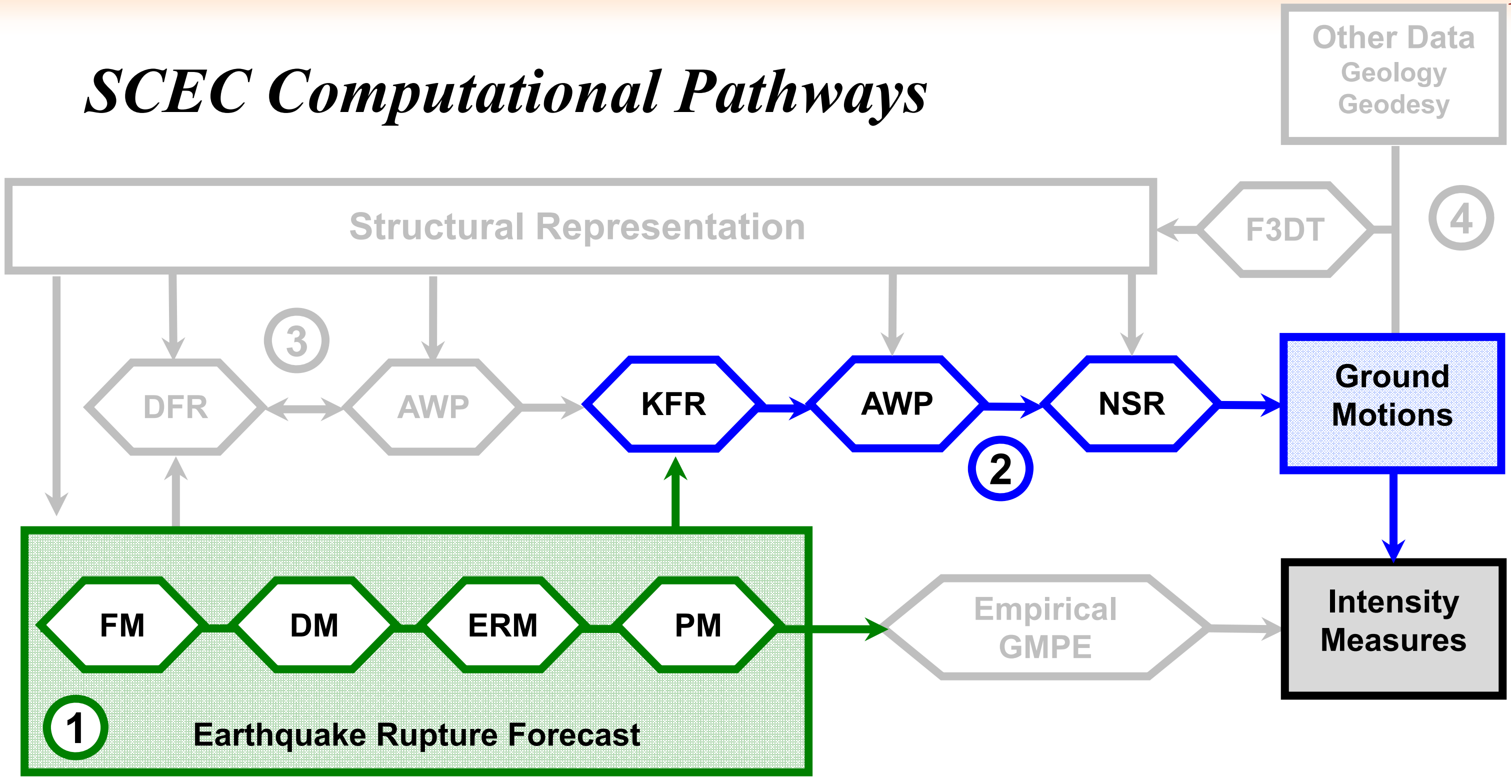
1 Uniform California Earthquake Rupture Forecast (UCERF3)

A main goal of SCEC HPC research is to replace the empirical GMPEs with physics-based ground motion models

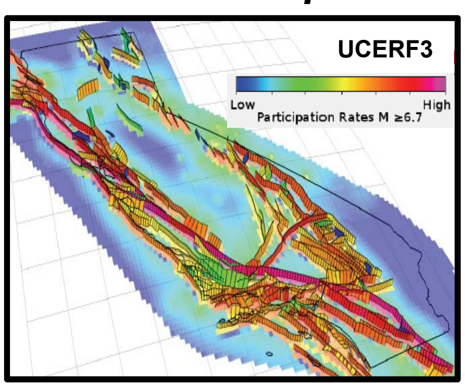


2014 National Seismic Hazard Maps

SCEC Computational Pathways

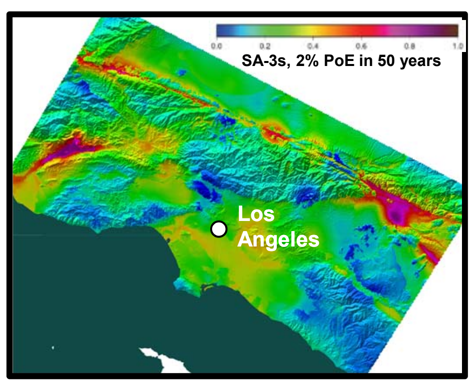


TACC *Stampede*



① Uniform California Earthquake Rupture Forecast (UCERF3)

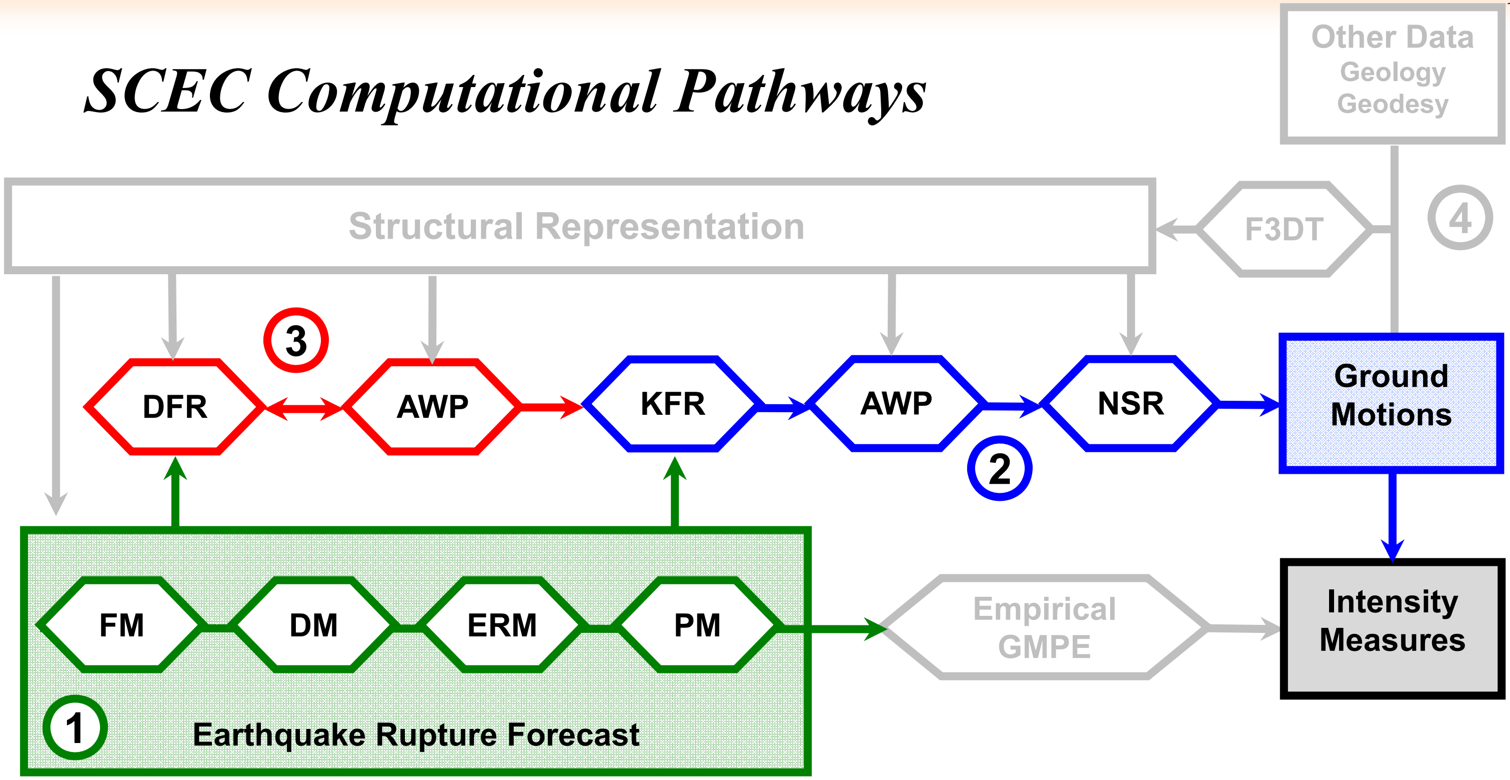
NCSA *Blue Waters*



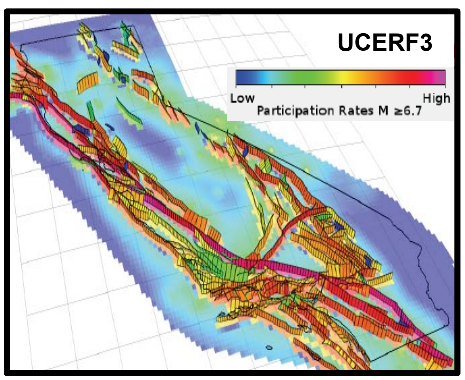
② CyberShake 14.2 seismic hazard model for LA region

KFR = Kinematic Fault Rupture
AWP = Anelastic Wave Propagation
NSR = Nonlinear Site Response
DFR = Dynamic Fault Rupture
F3DT = Full-3D Tomography

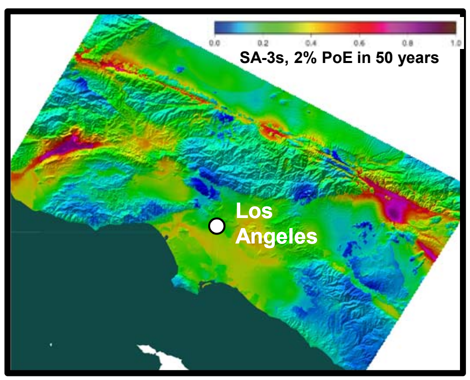
SCEC Computational Pathways



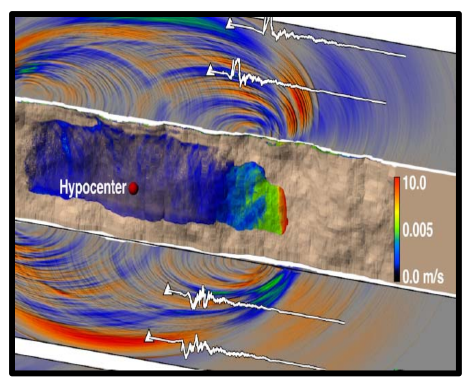
TACC *Stampede*	NCSA *Blue Waters*	OLCF *Titan*



(1) Uniform California Earthquake Rupture Forecast (UCERF3)



(2) CyberShake 14.2 seismic hazard model for LA region



(3) Dynamic rupture model of fractal roughness on SAF

KFR = Kinematic Fault Rupture

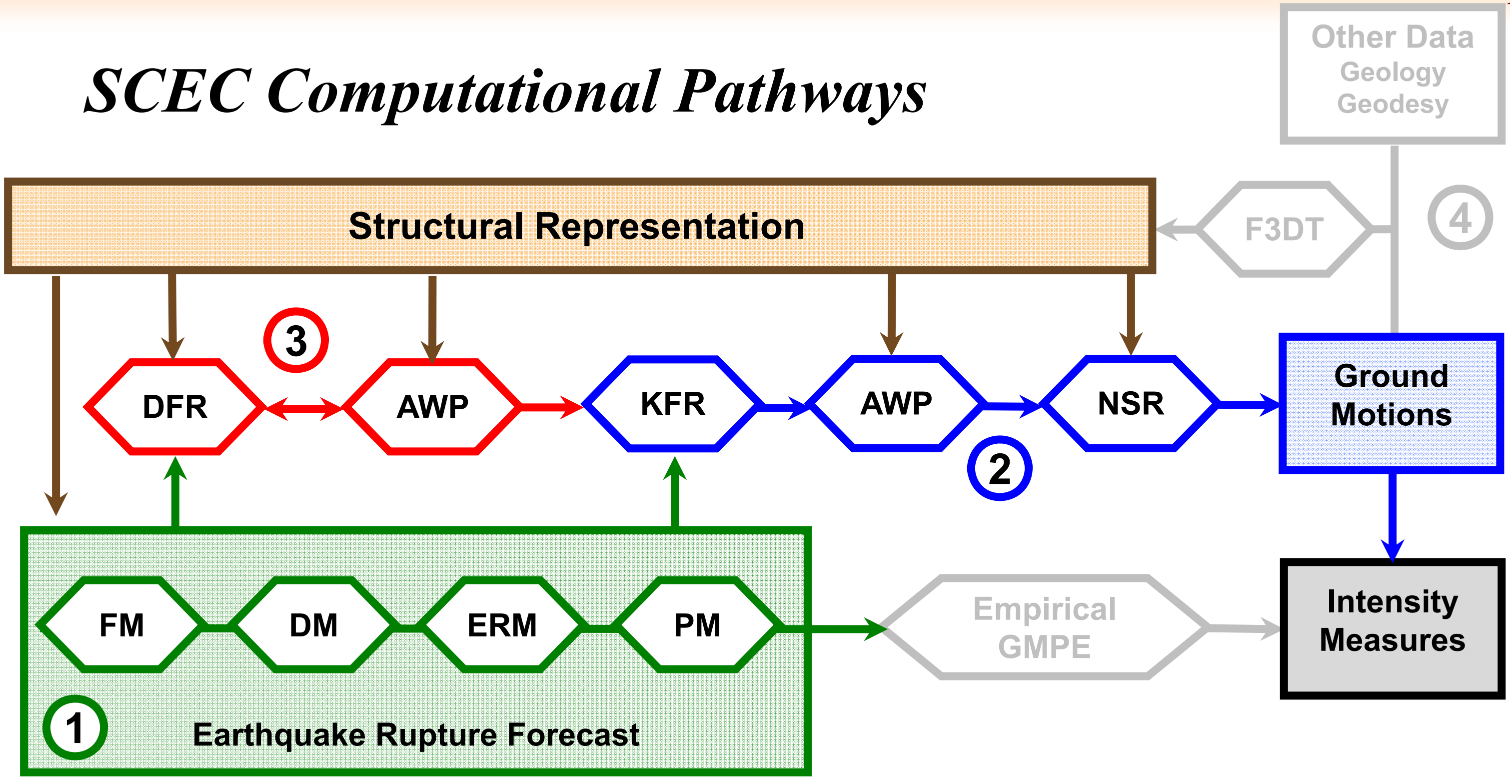
AWP = Anelastic Wave Propagation

NSR = Nonlinear Site Response

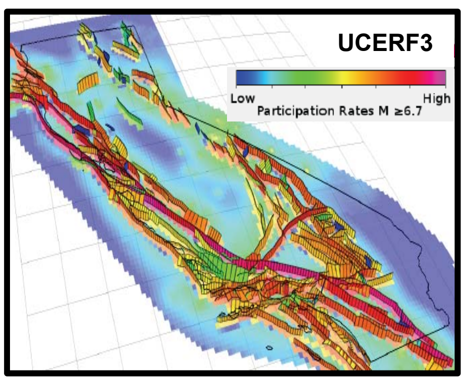
DFR = Dynamic Fault Rupture

F3DT = Full-3D Tomography

SCEC Computational Pathways

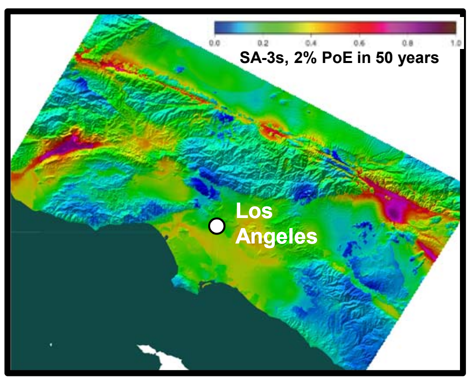


TACC *Stampede*



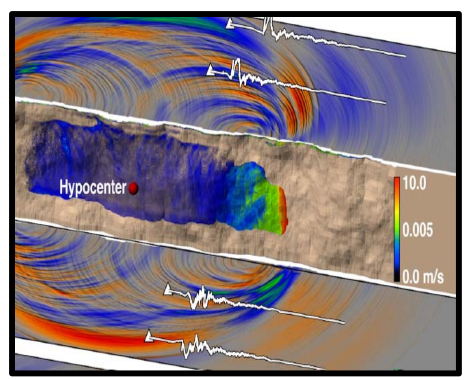
① Uniform California Earthquake Rupture Forecast (UCERF3)

NCSA *Blue Waters*



② CyberShake 14.2 seismic hazard model for LA region

OLCF *Titan*



③ Dynamic rupture model of fractal roughness on SAF

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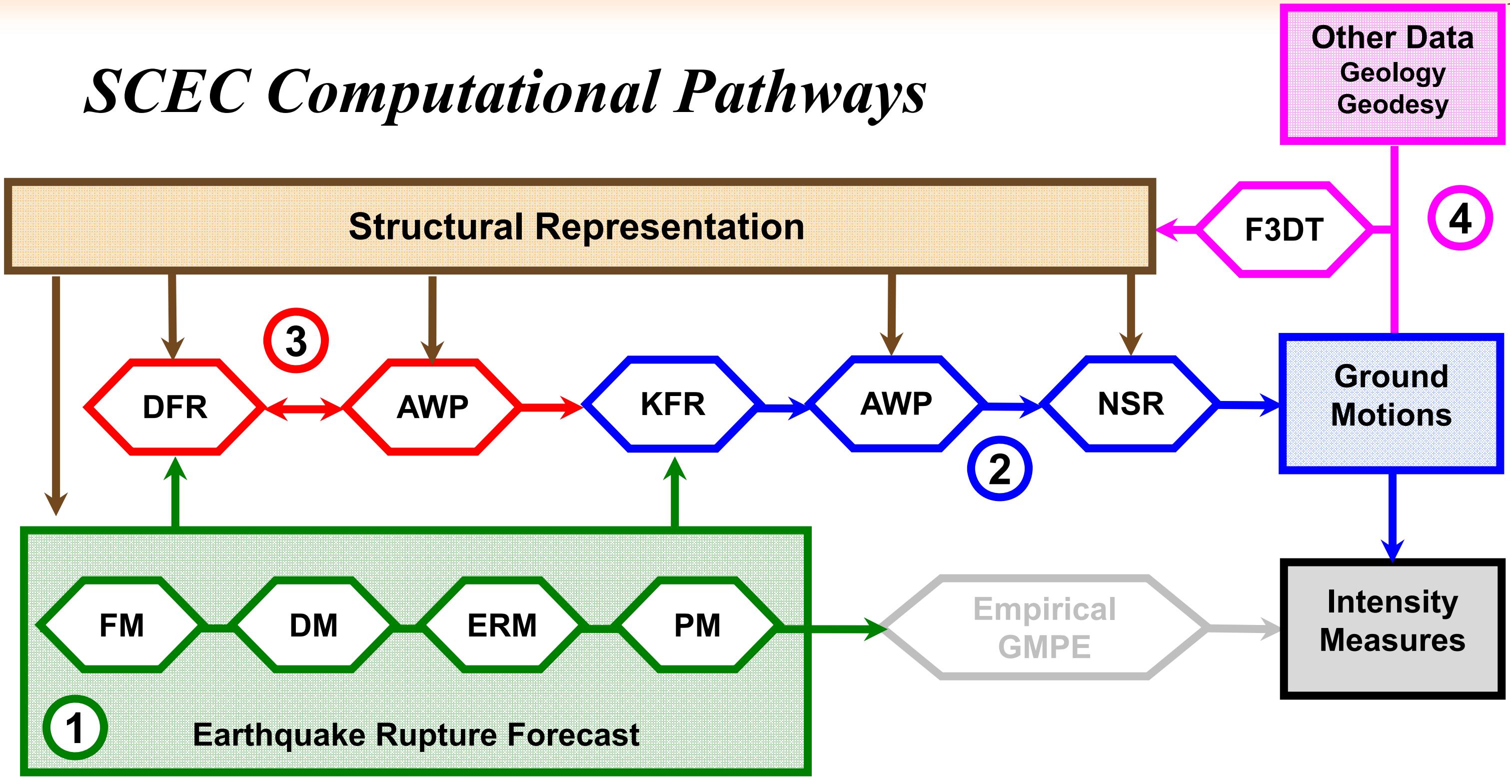
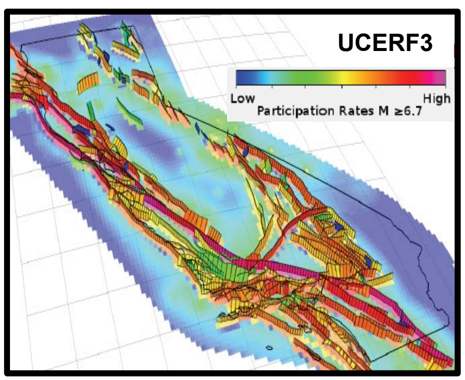
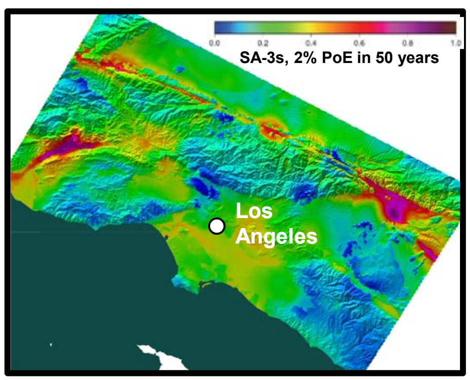


TACC *Stampede*



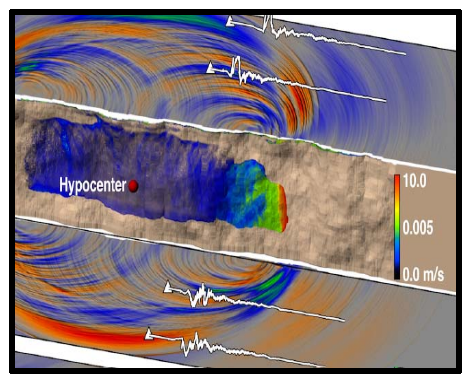
1 Uniform California Earthquake Rupture Forecast (UCERF3)

NCSA *Blue Waters*



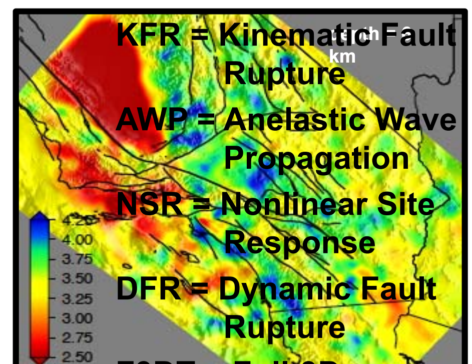
2 CyberShake 14.2 seismic hazard model for LA region

OLCF *Titan*



3 Dynamic rupture model of fractal roughness on SAF

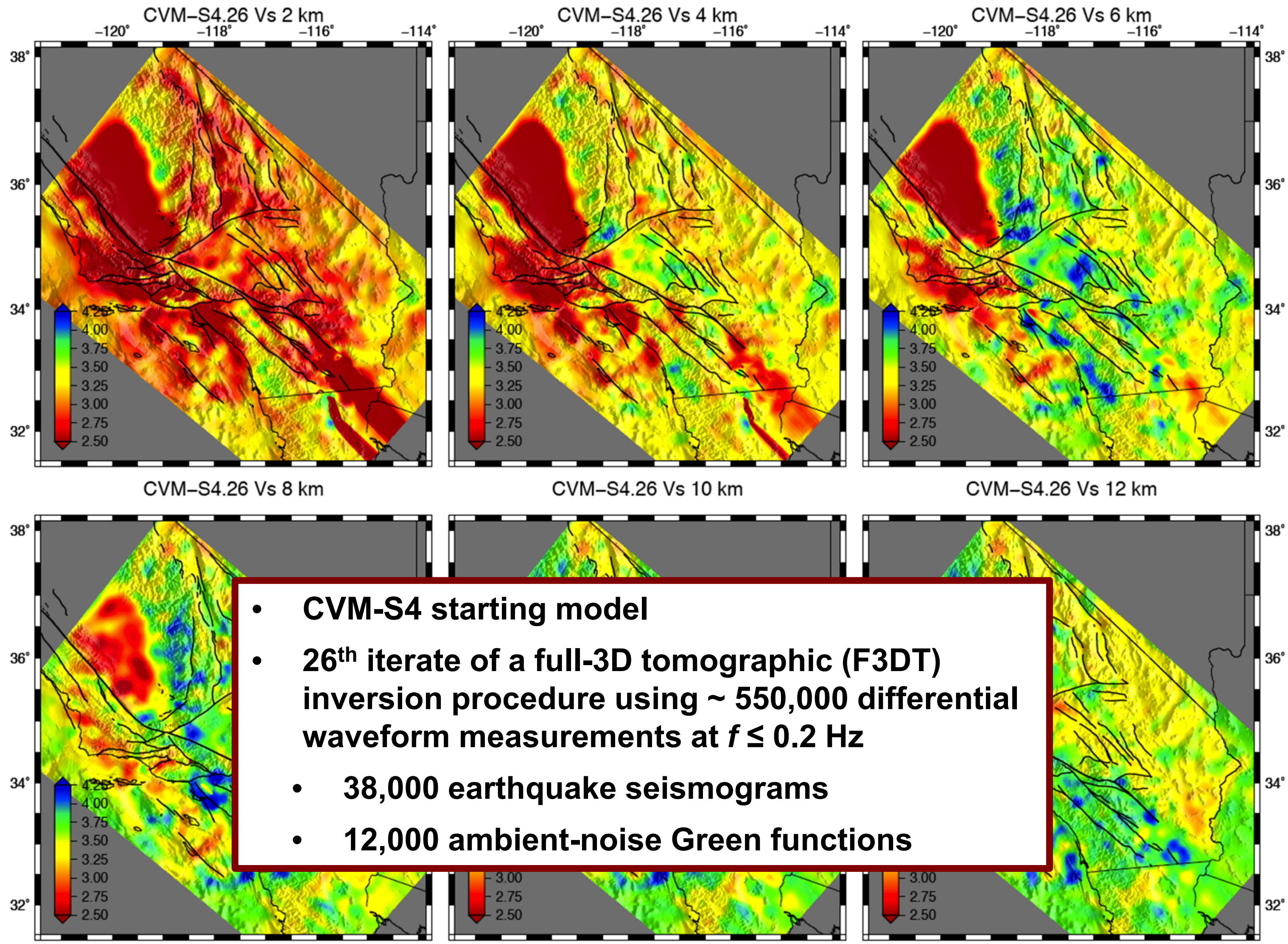
ALCF *Mira*



4 Full-3D tomographic model CVM-S4.26 of S. California

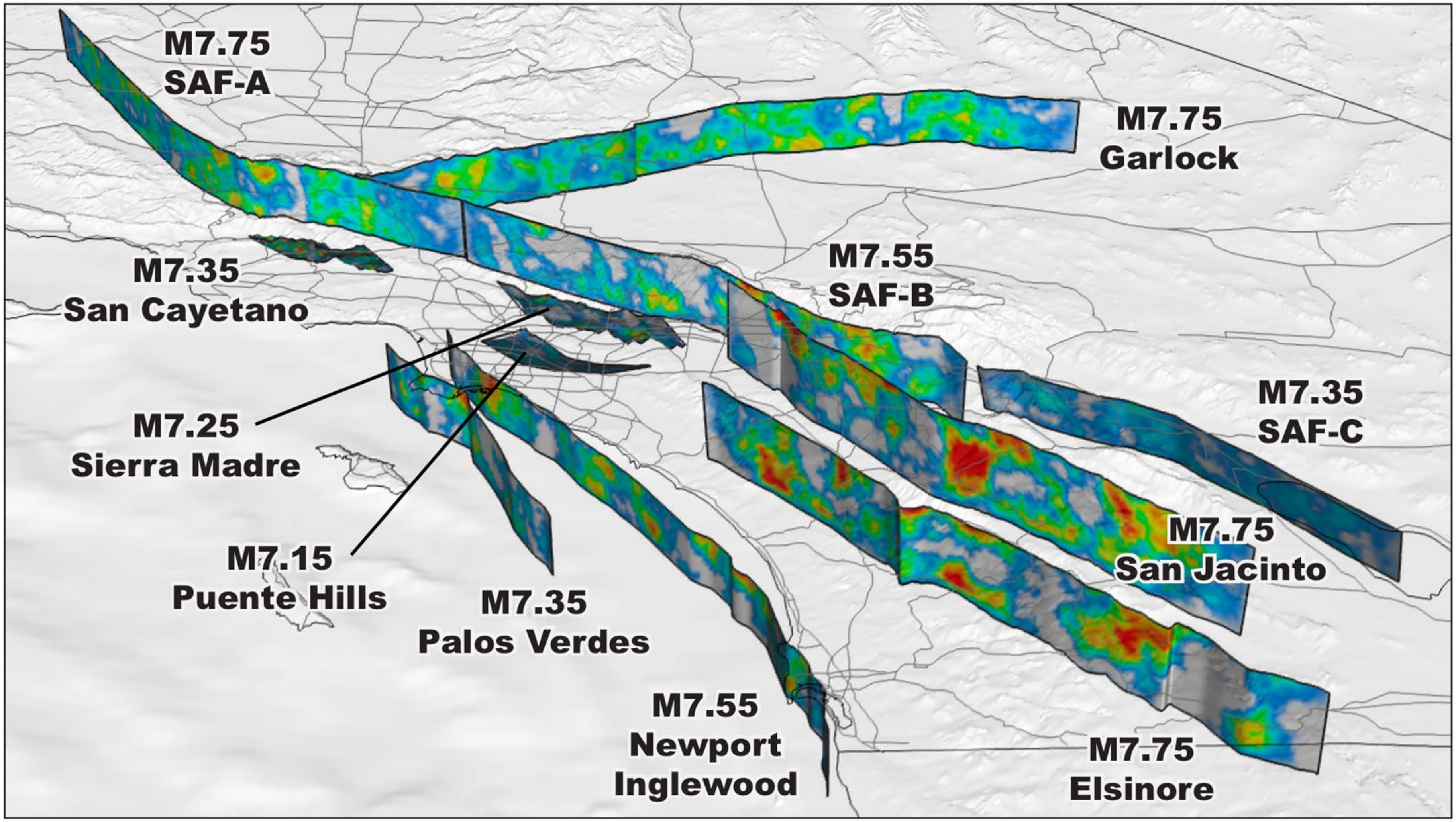
CVM-S4.26

Full-3D tomography model of Southern California crustal structure



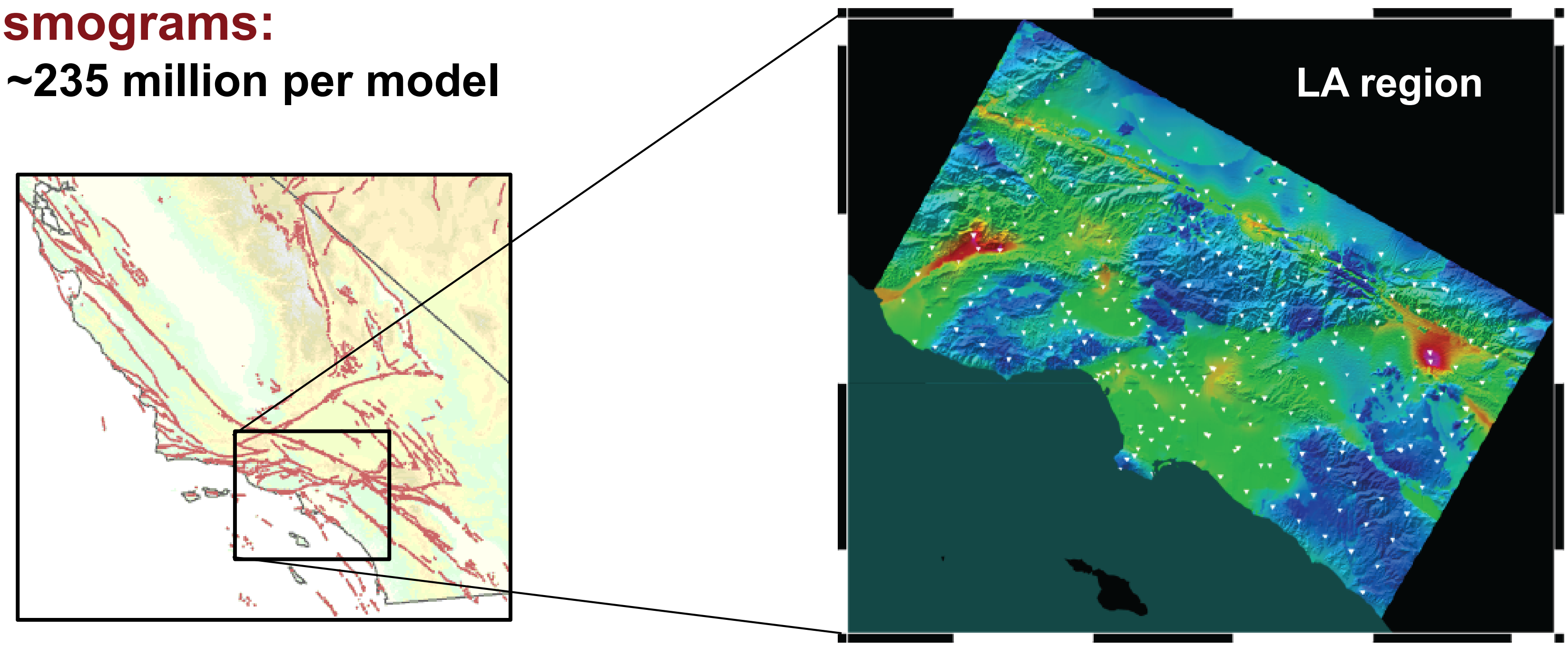
- **CVM-S4 starting model**
- **26th iterate of a full-3D tomographic (F3DT) inversion procedure using ~ 550,000 differential waveform measurements at *f* ≤ 0.2 Hz**
  - **38,000 earthquake seismograms**
  - **12,000 ambient-noise Green functions**

Examples of CyberShake Rupture Models

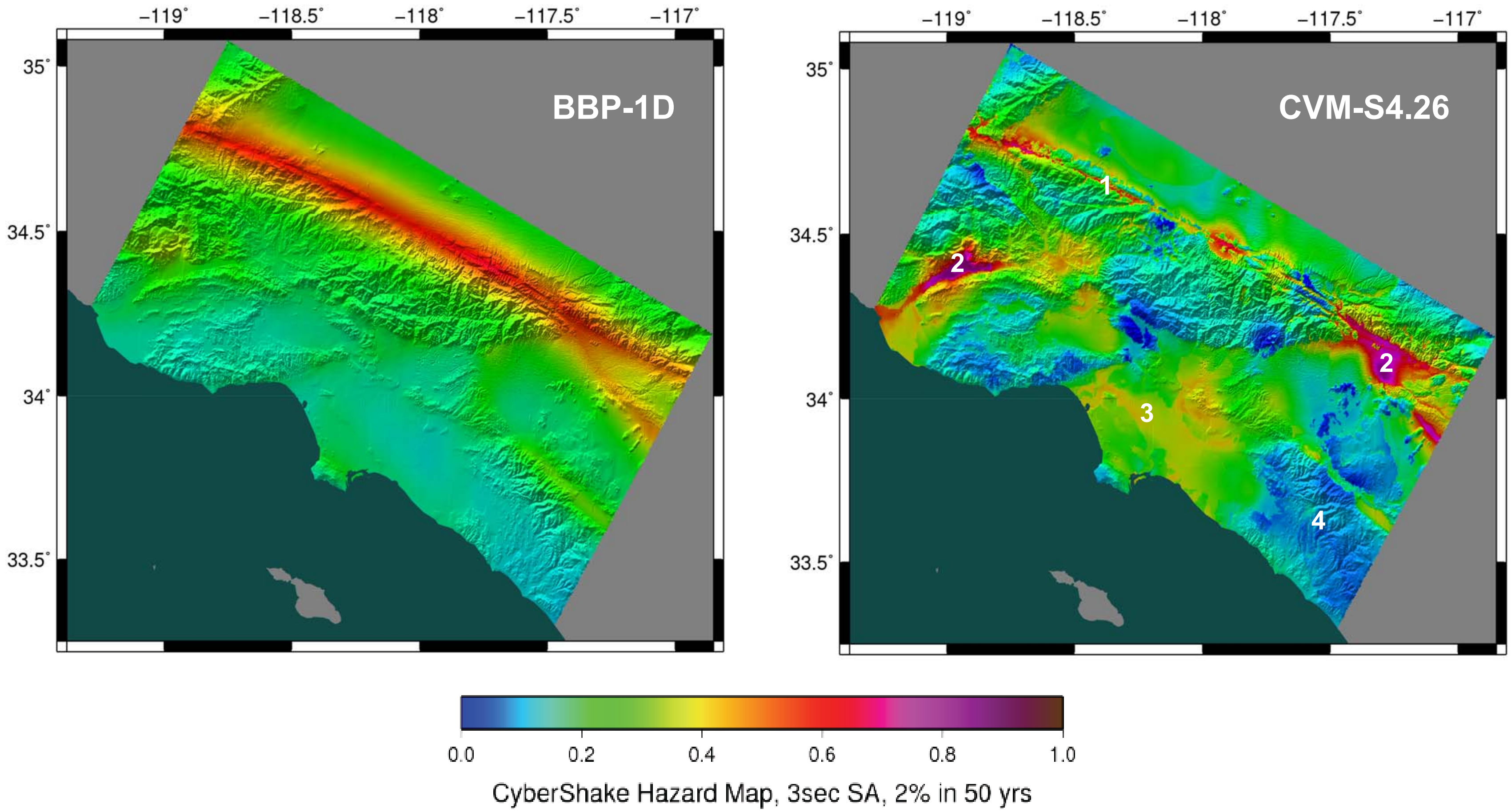


CyberShake Hazard Model

- **3D crustal model:**
  - **CVM-S4.26**
- **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**

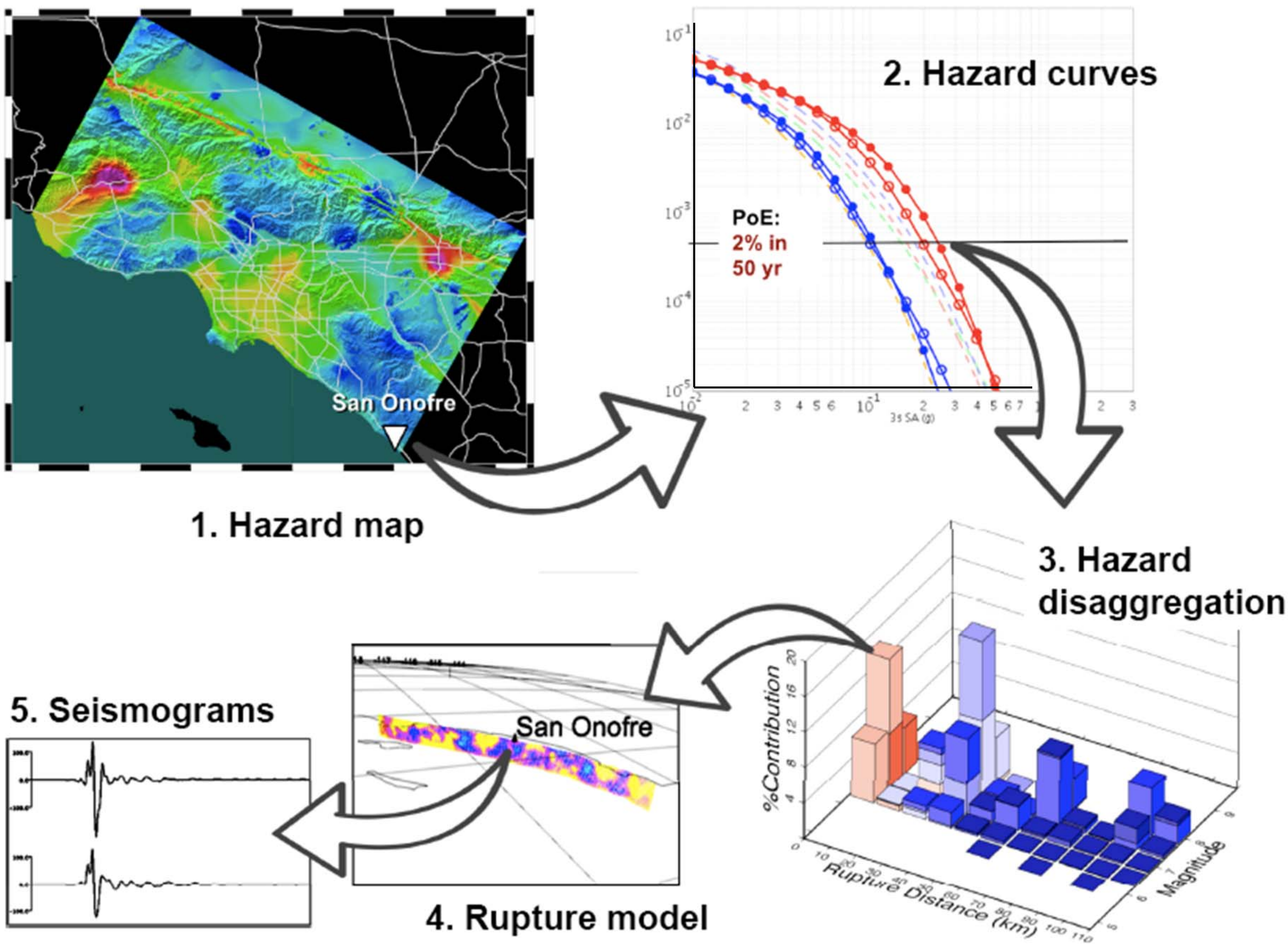


Comparison of 1D and 3D CyberShake Models for the Los Angeles Region

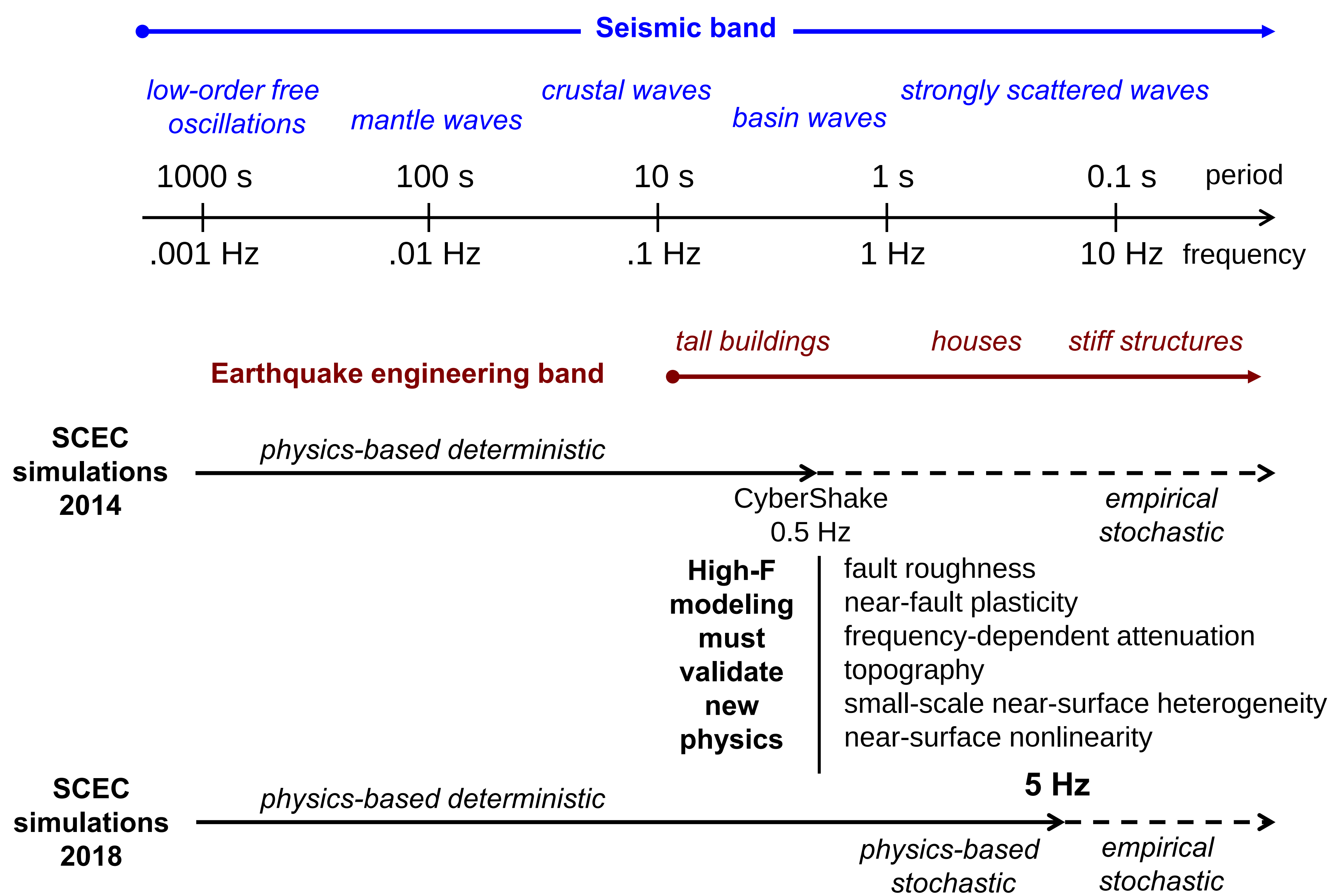


1. **lower near-fault intensities due to 3D scattering**
2. **much higher intensities in near-fault basins**
3. **higher intensities in the Los Angeles basins**
4. **lower intensities in hard-rock areas**

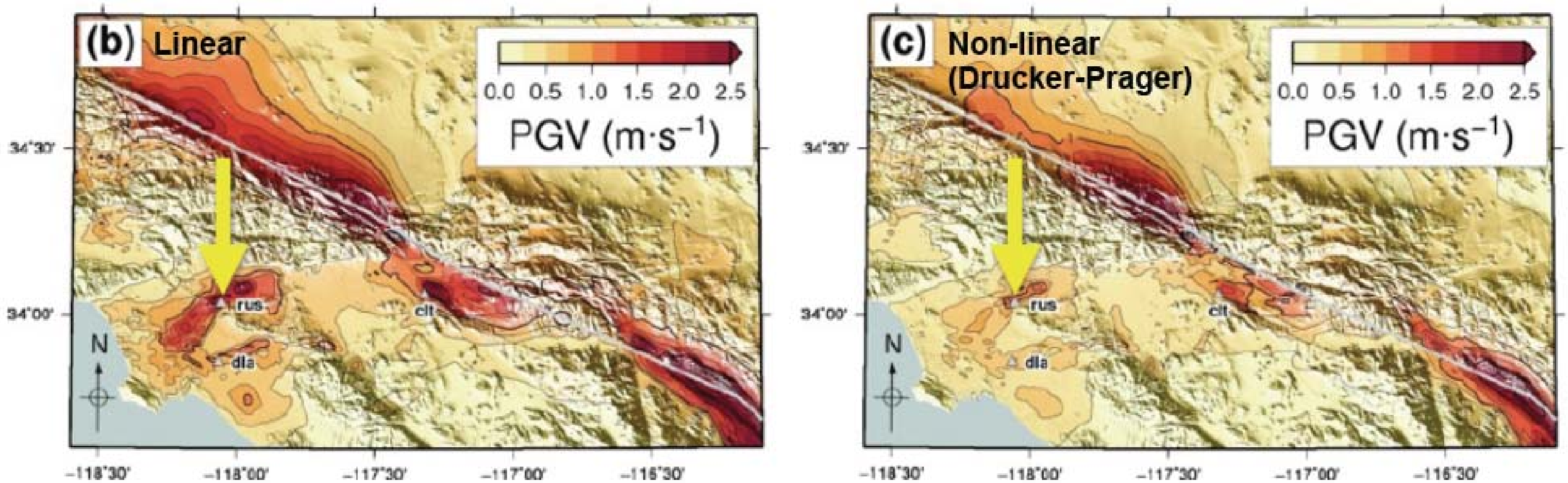
CyberShake Platform: Physics-Based PSHA



High-F Project



High-F Project



SCEC simulations 2014

physics-based deterministic → CyberShake 0.5 Hz - - - → *empirical stochastic*

High-F modeling must validate new physics

- fault roughness
- near-fault plasticity
- frequency-dependent attenuation
- topography
- small-scale near-surface heterogeneity
- near-surface nonlinearity

5 Hz

SCEC simulations 2018

physics-based deterministic → *physics-based stochastic* - - - → *empirical stochastic*

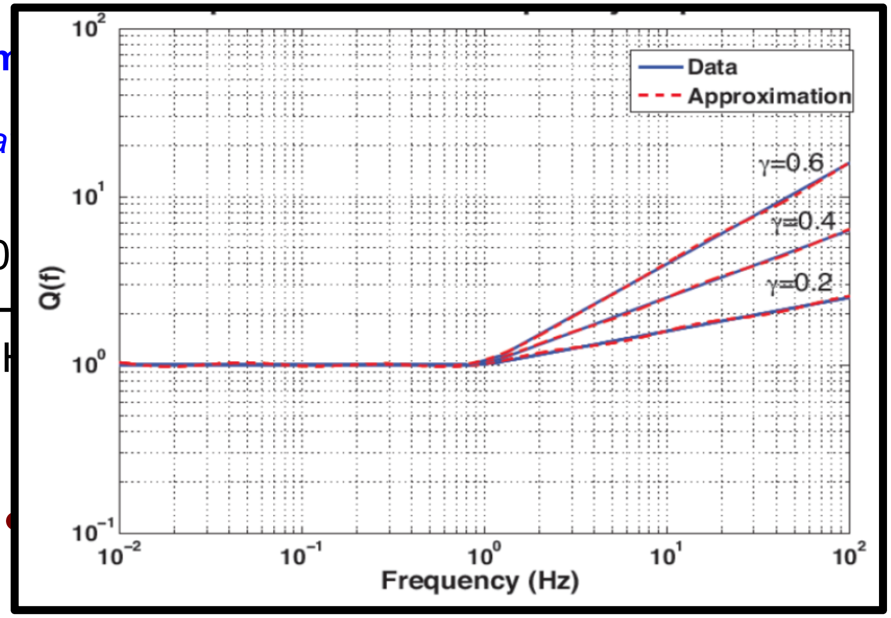
High-F Project

Seism...

low-order free oscillations — *mantle waves* — *crustal wa...*

1000 s — 100 s — 10...

.001 Hz — .01 Hz — .1 H...



Earthquake engineering band

SCEC simulations 2014 — *physics-based deterministic* → CyberShake 0.5 Hz - - - → *empirical stochastic*

High-F modeling must validate new physics

- fault roughness
- near-fault plasticity
- frequency-dependent attenuation
- topography
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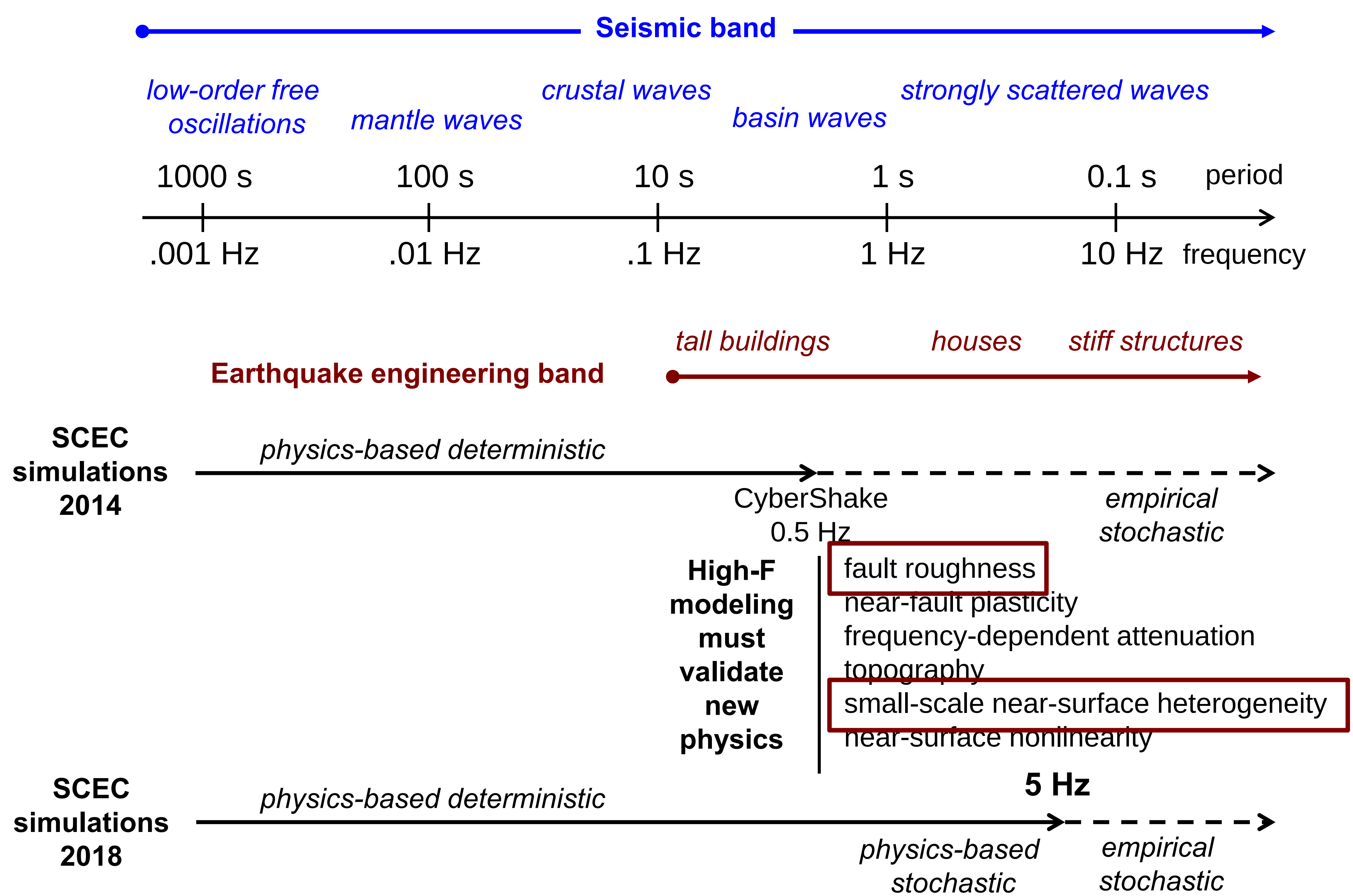
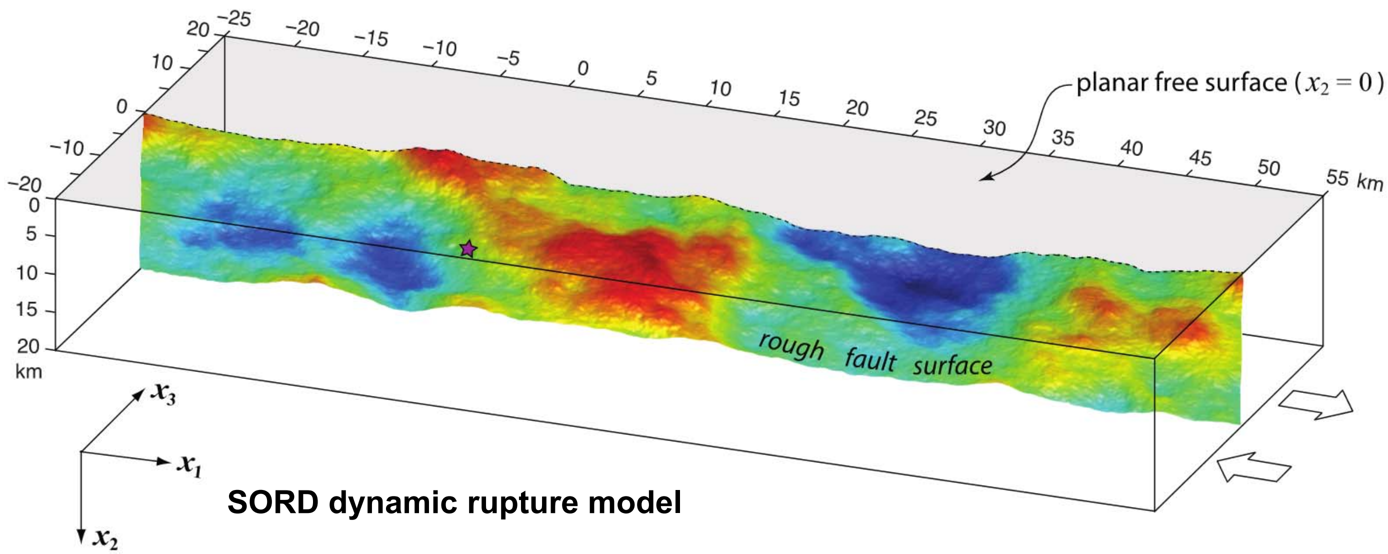
SCEC simulations 2018 — *physics-based deterministic* → **5 Hz** *physics-based stochastic* - - - → *empirical stochastic*

High-F Project

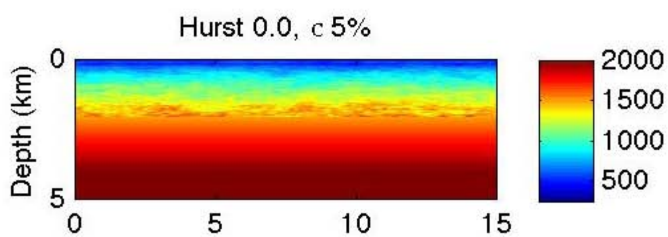


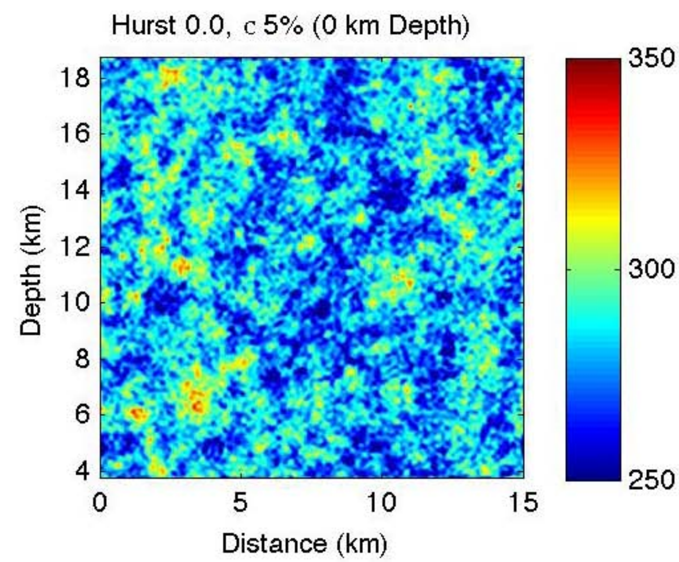
AWP-ODC Titan Runs

rough fault, *f*-dependent *Q*, near-surface heterogeneity



SORD dynamic rupture model





UCVM stochastic heterogeneity model

Visualization Of Deterministic High-Frequency Ground Motions From Simulations Of Dynamic Rupture Along Rough Faults With And Without Medium Heterogeneity Using Petascale Heterogeneous Supercomputers

AWP-ODC Titan Runs

rough fault, *f*-dependent *Q*, near-surface heterogeneity

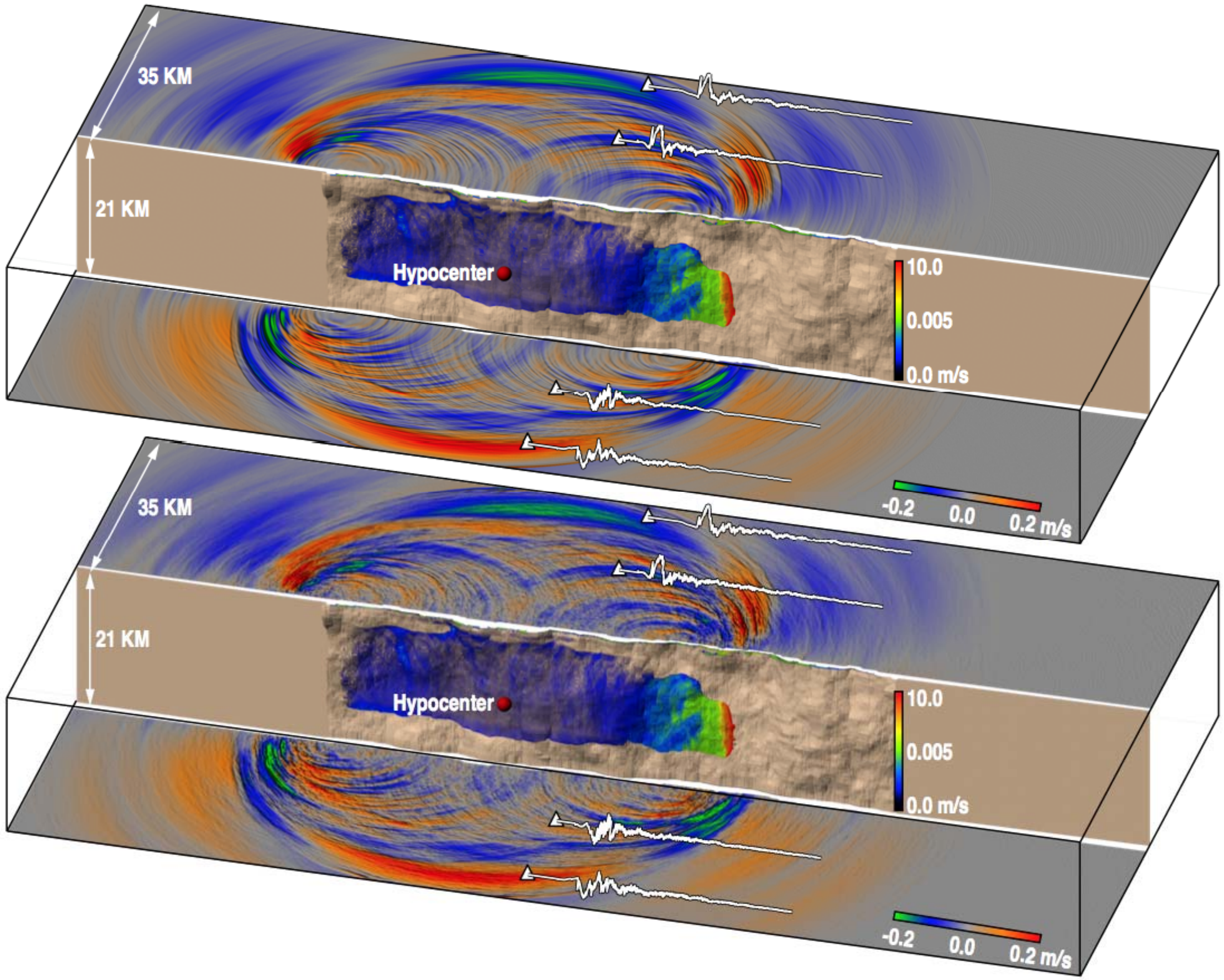
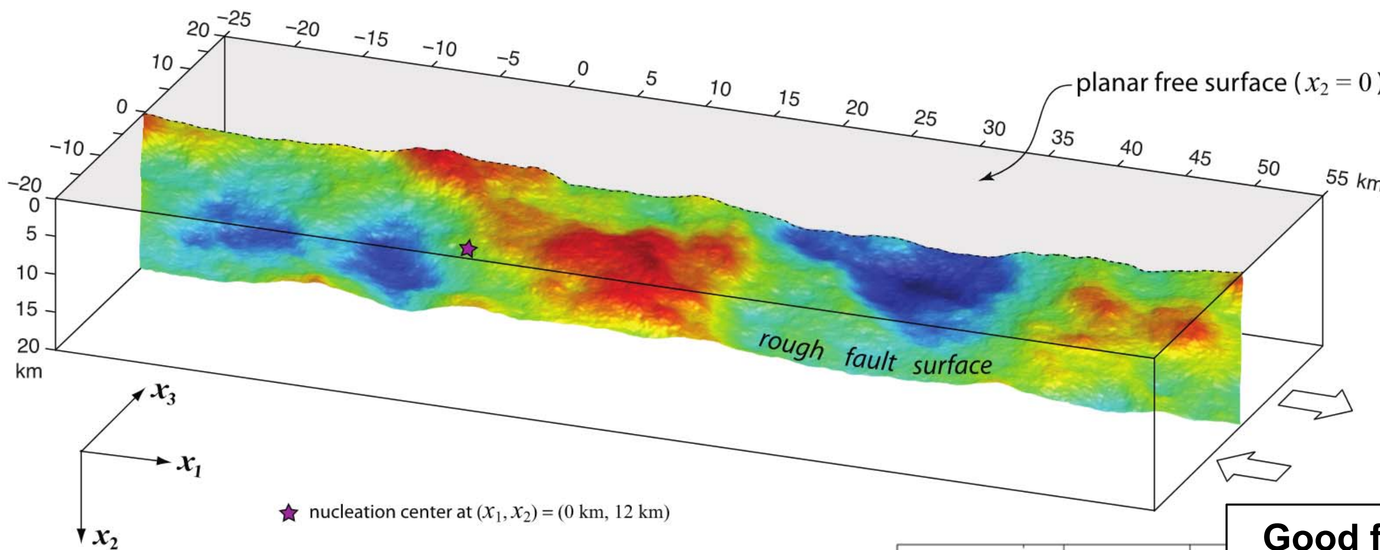
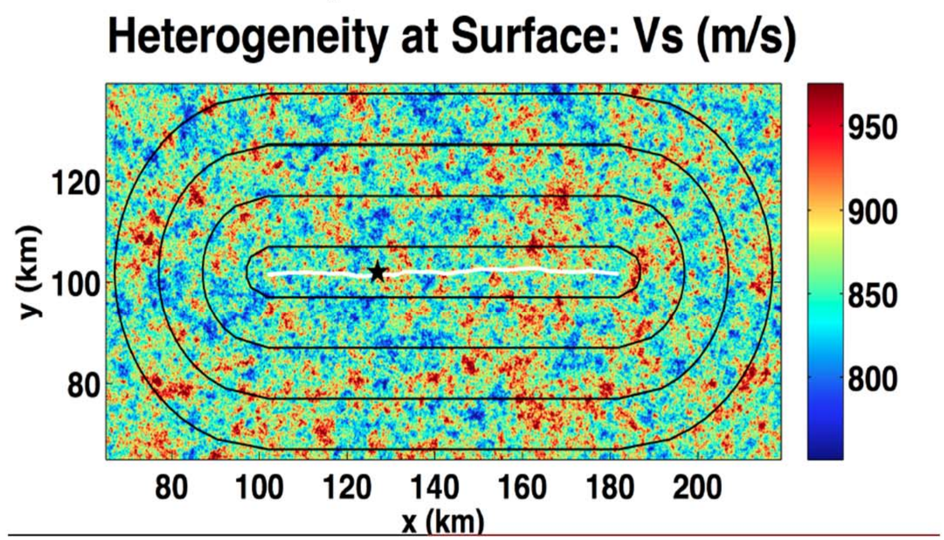


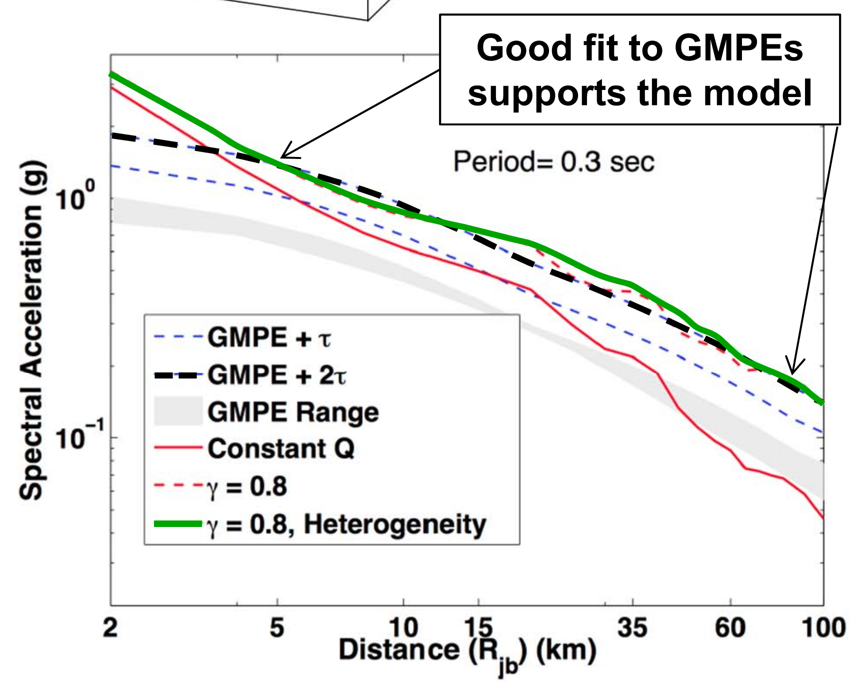
Image Credit: Kim Olsen, Yifeng Cui, Amit Chourasia

AWP-ODC Titan Runs

rough fault, *f*-dependent *Q*, near-surface heterogeneity

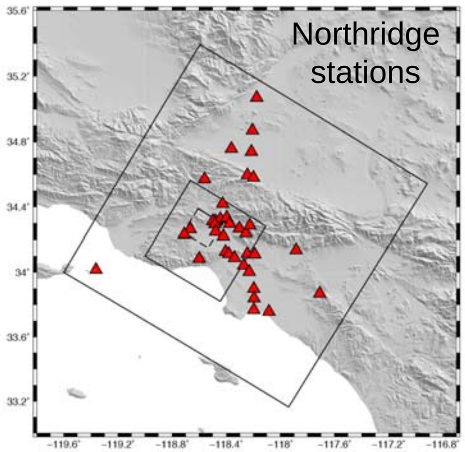


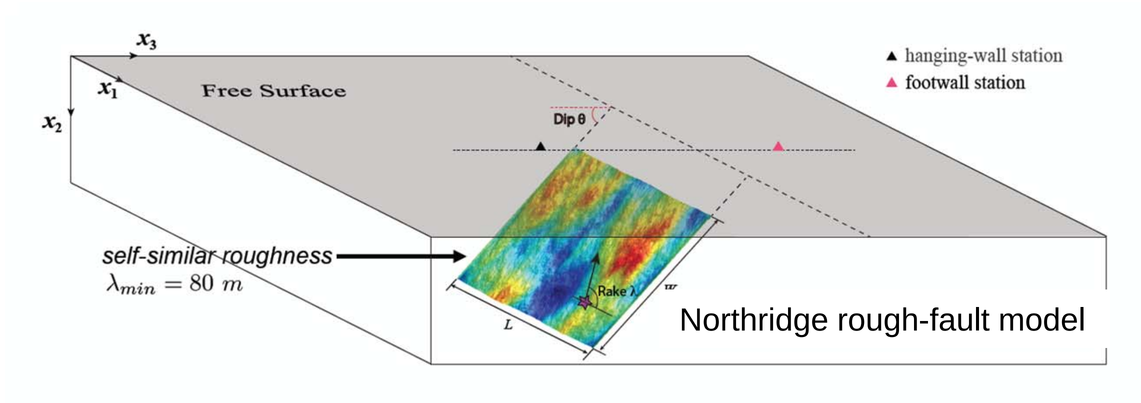


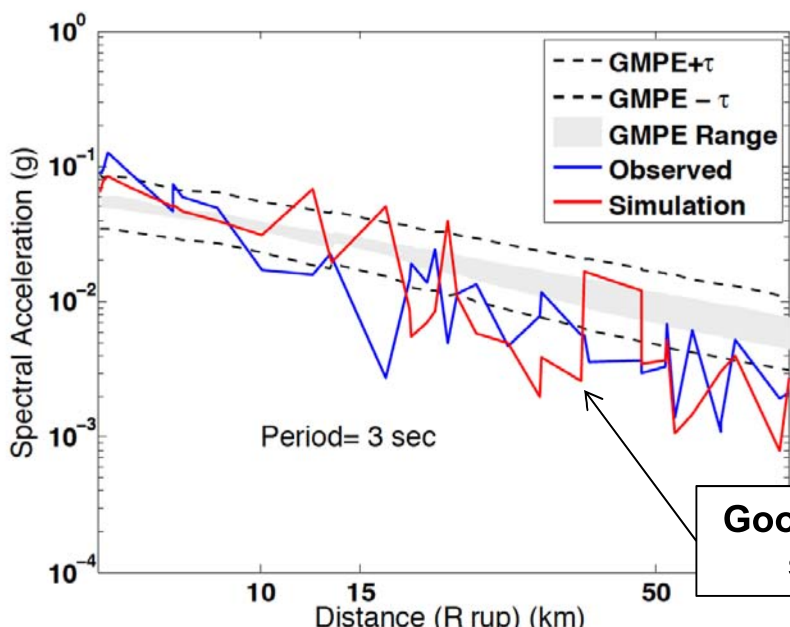


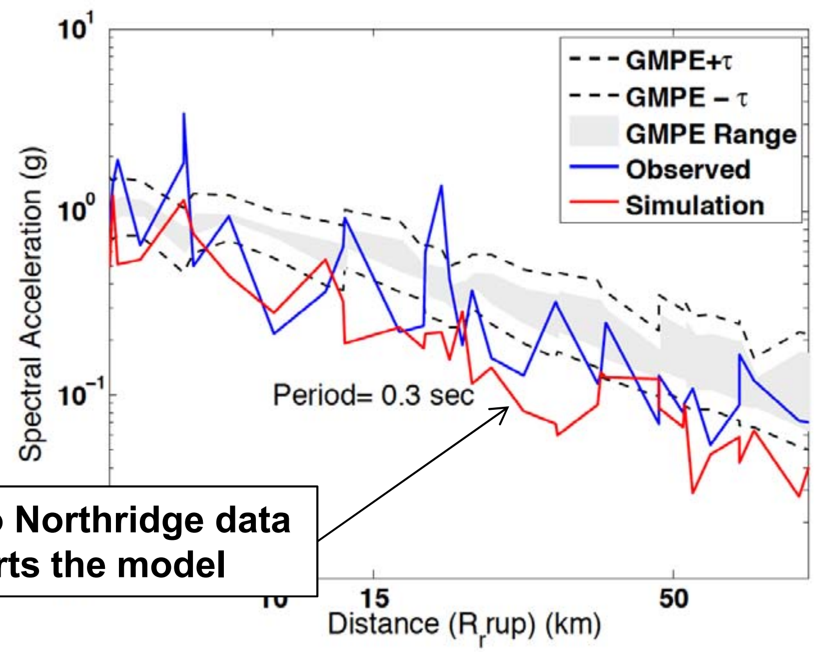
01/17/94 Northridge Earthquake (M6.7)

rough fault, f-dependent Q, near-surface heterogeneity





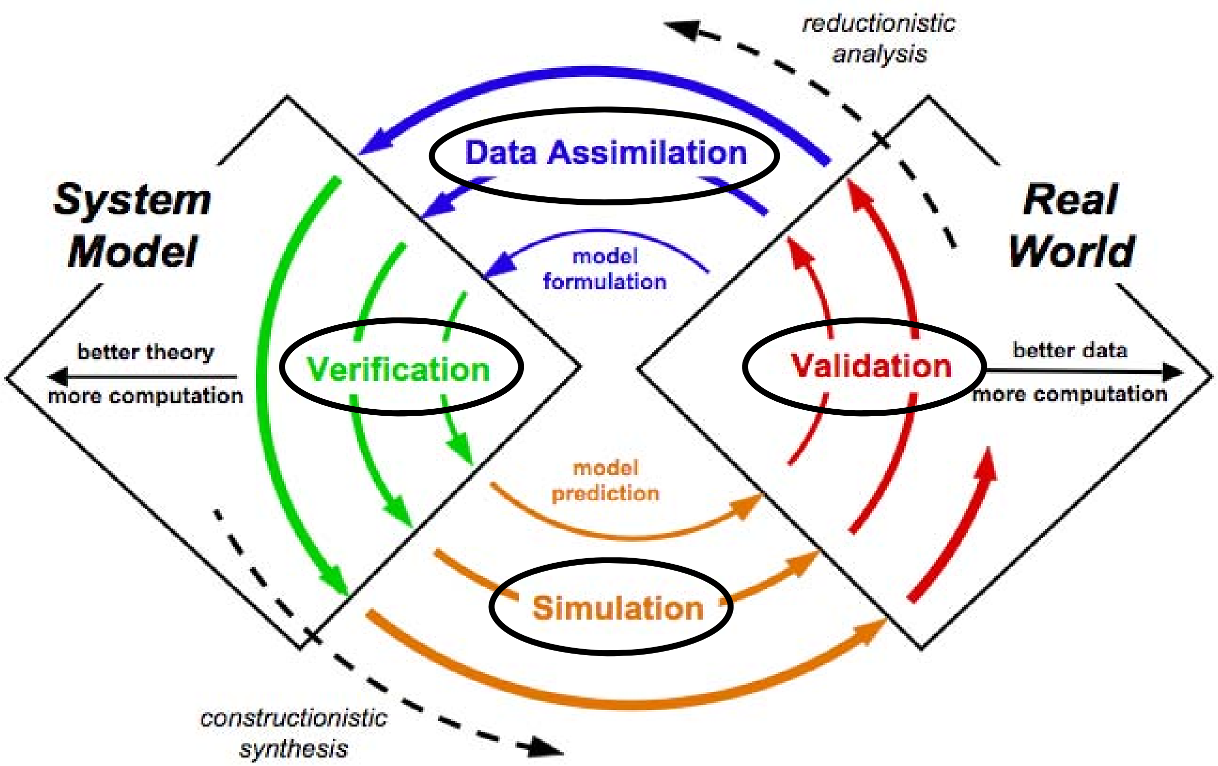




Good fit to Northridge data supports the model

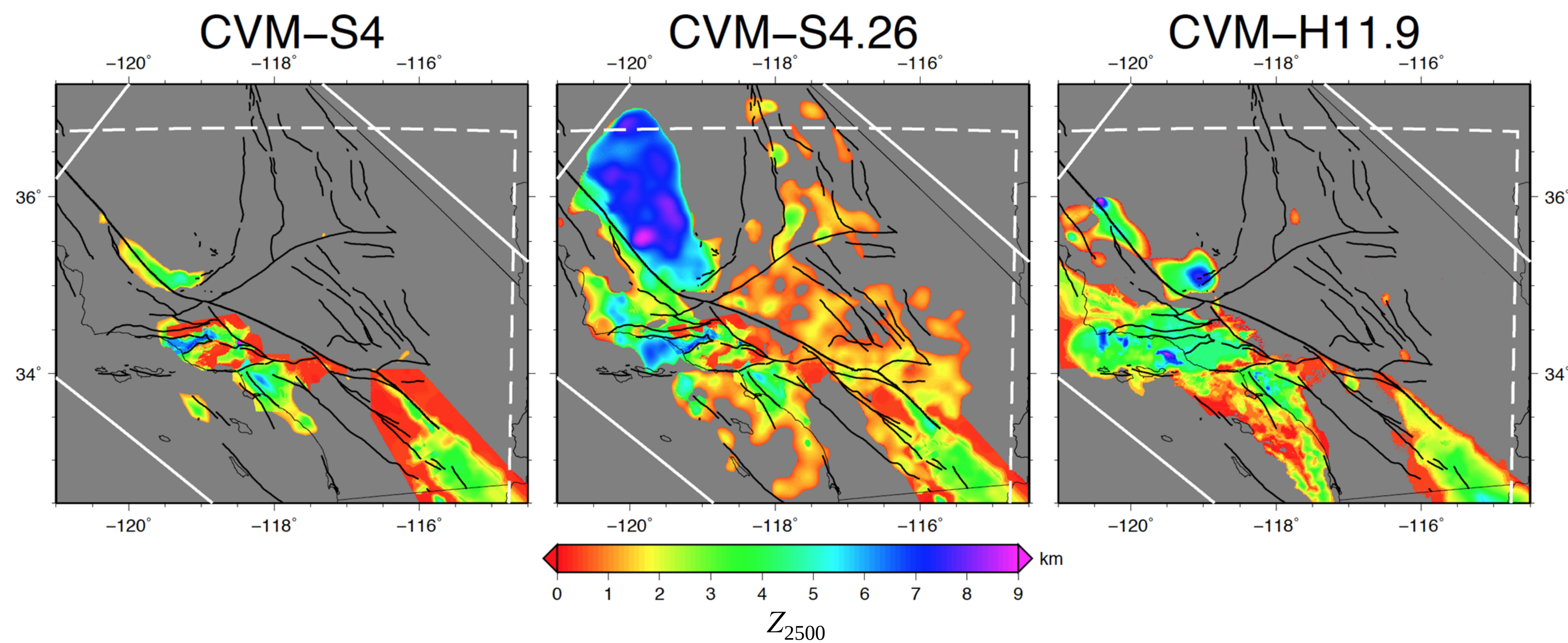
Inference Spiral of System Science

- Earthquake system science requires an iterative, computationally intense process of model formulation and verification, simulation-based predictions, validation against observations, and data assimilation to improve the model



- As models become more complex and new data bring in more information, we require ever increasing computational resources

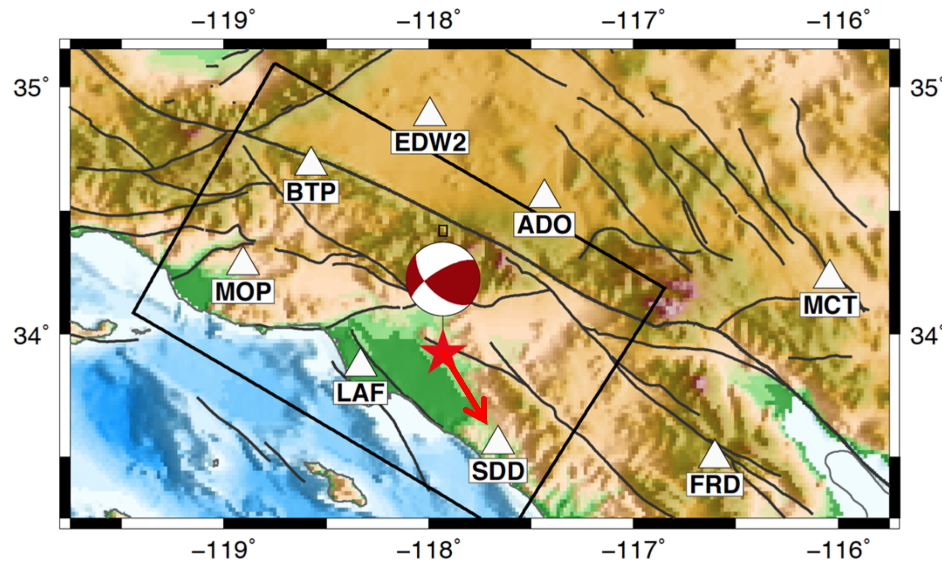
Basin Structures

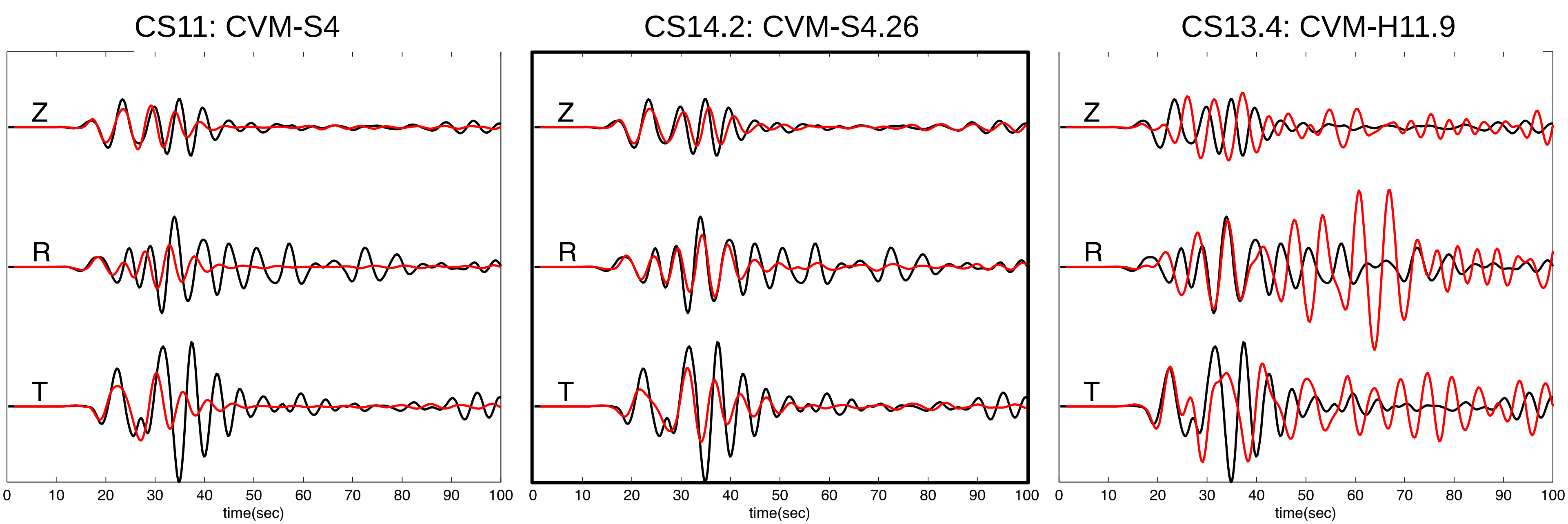


Z_{2500} : iso-velocity surfaces at V_S = 2.5 km/s

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

Station SDD
Observed in black
Synthetic in red





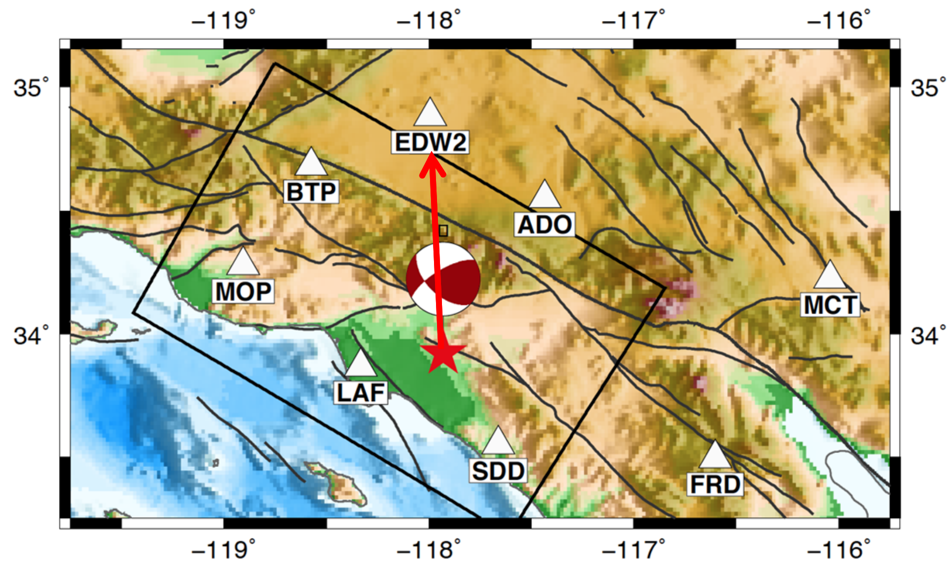
Southern California
Earthquake Center

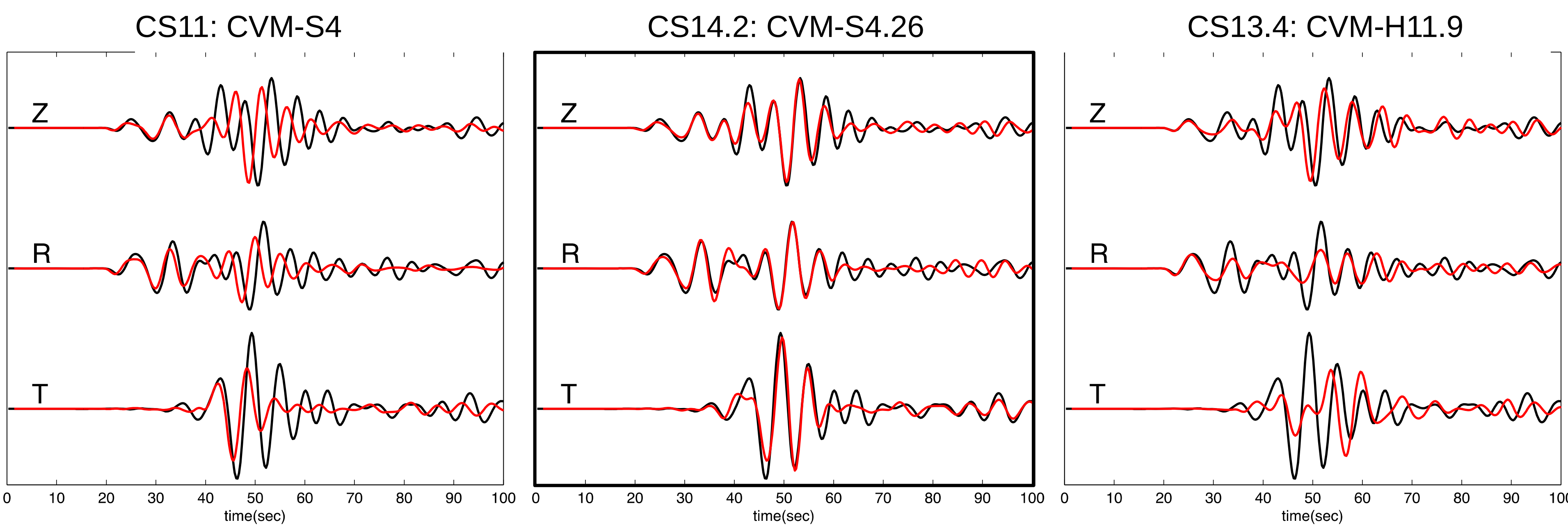
03/28/14 La Habra Earthquake (M5.1)

Station EDW2

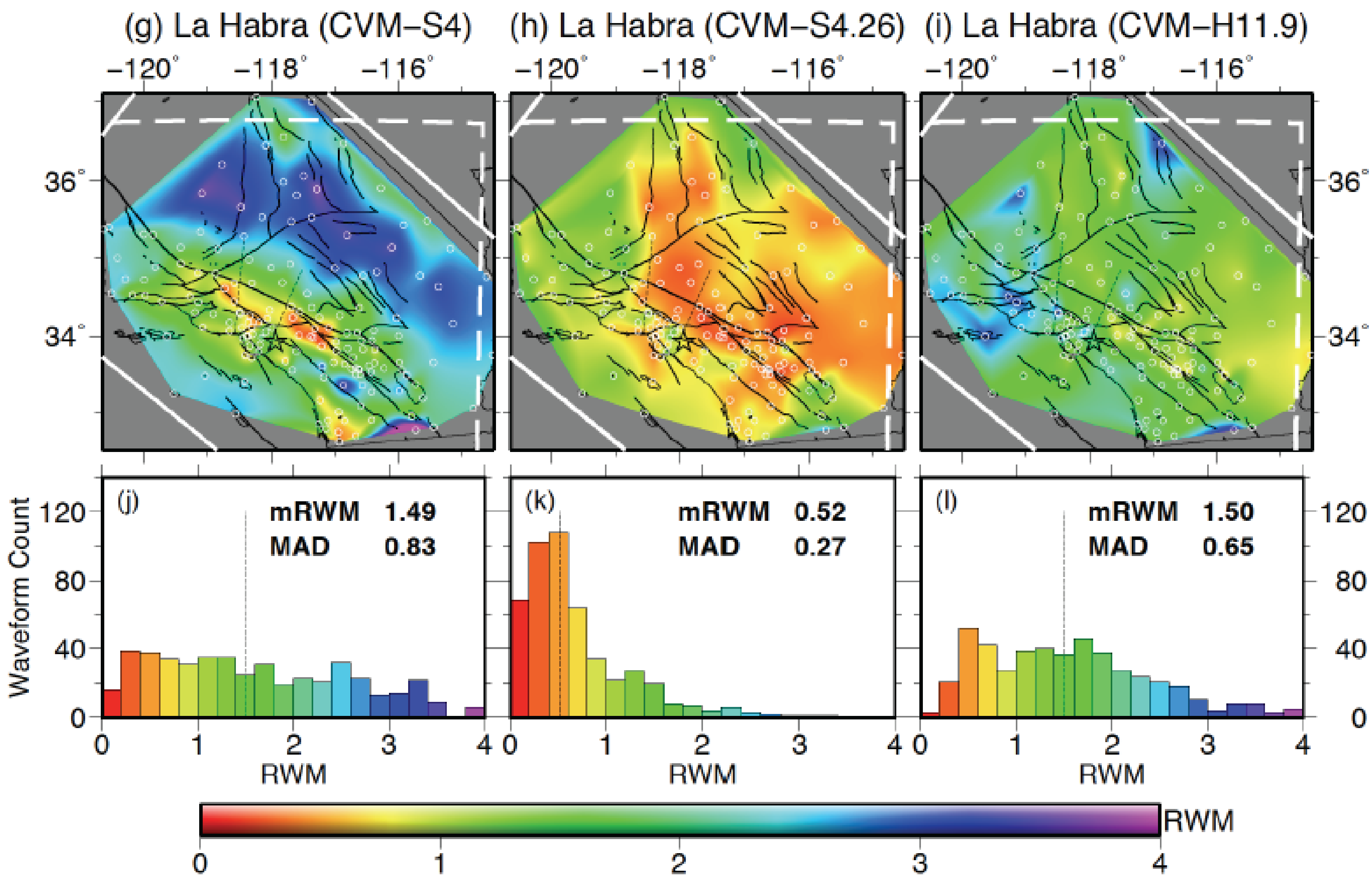
Observed in black

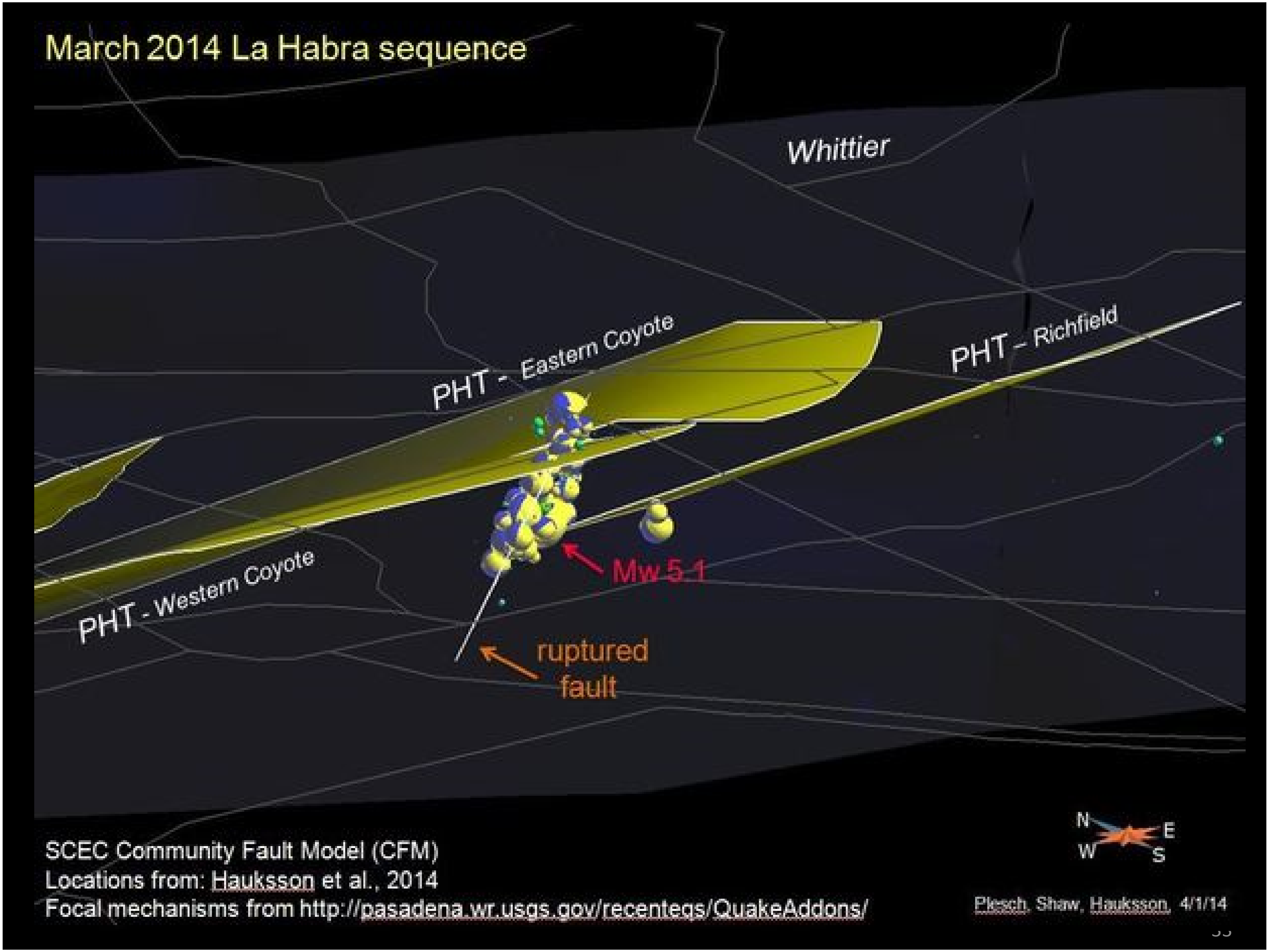
Synthetic in red





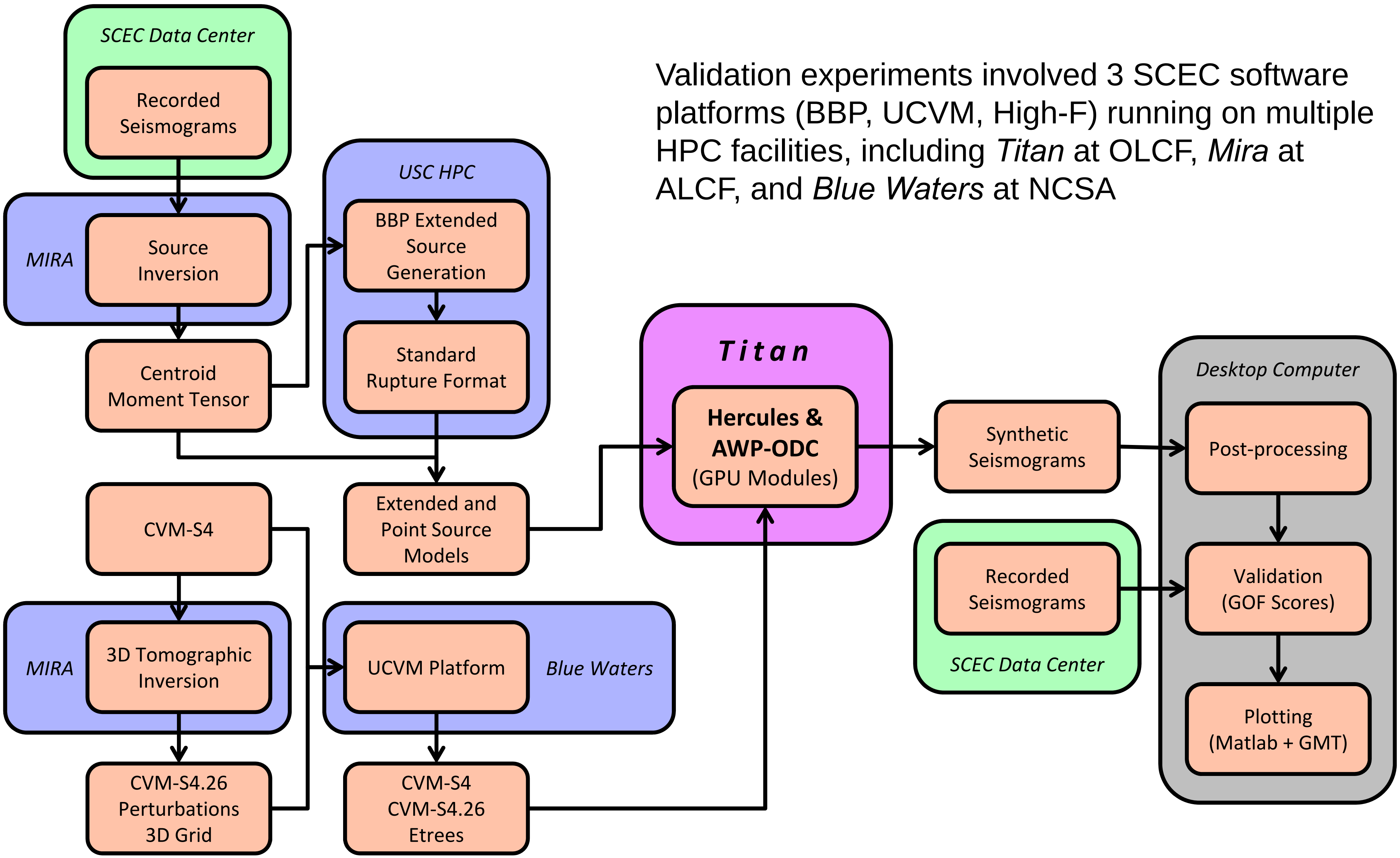
03/28/14 La Habra Earthquake (M5.1)




March 2014 La Habra sequence
Whittier
PHT - Eastern Coyote
PHT – Richfield
PHT - Western Coyote
Mw 5.1
ruptured fault
N
E
W
S
SCEC Community Fault Model (CFM)
Locations from: Hauksson et al., 2014
Focal mechanisms from http://pasadena.wr.usgs.gov/recenteqs/QuakeAddons/
Plesch, Shaw, Hauksson, 4/1/14

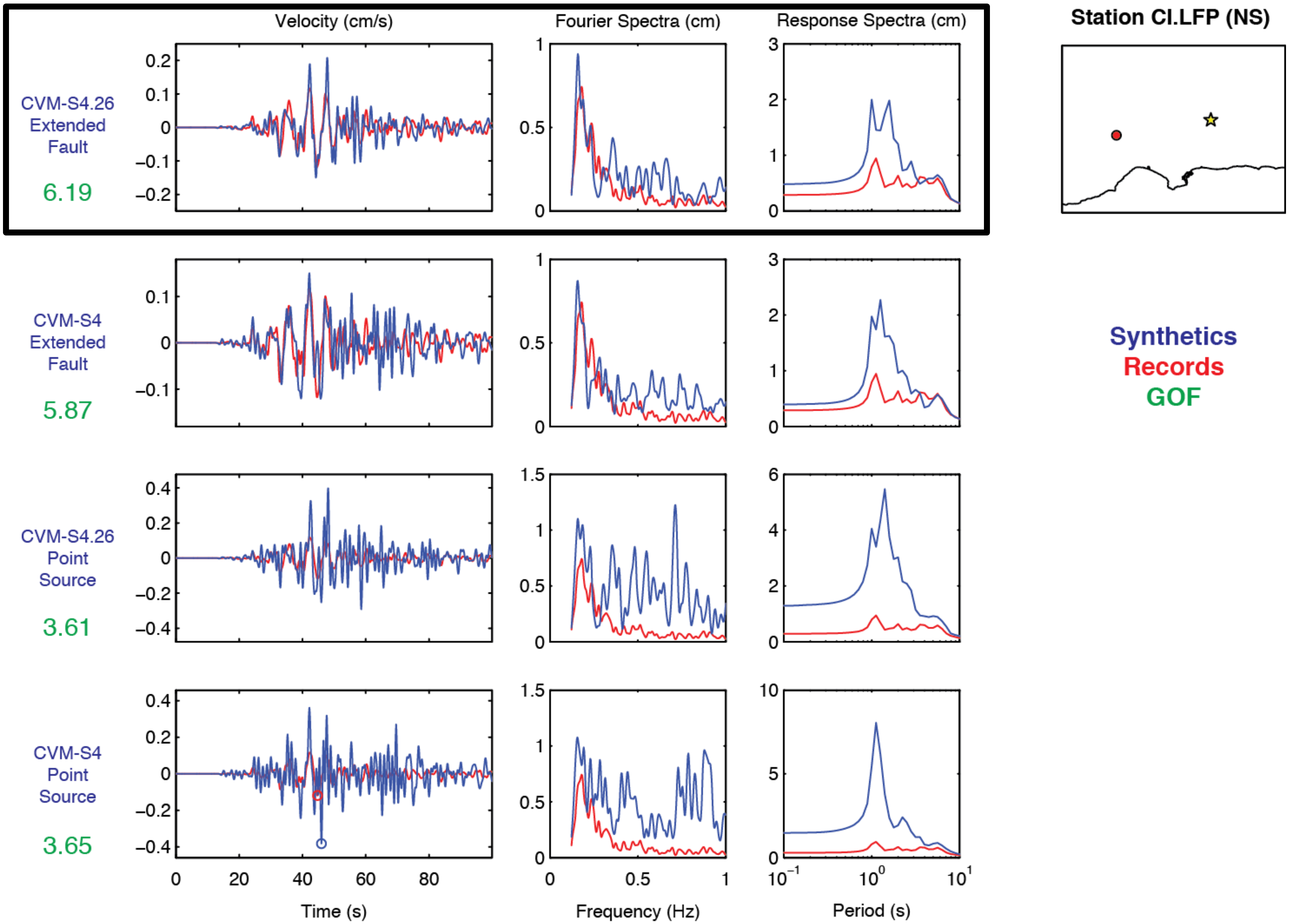
Workflow for High-F Validation Experiments

Validation experiments involved 3 SCEC software platforms (BBP, UCVM, High-F) running on multiple HPC facilities, including *Titan* at OLCF, *Mira* at ALCF, and *Blue Waters* at NCSA



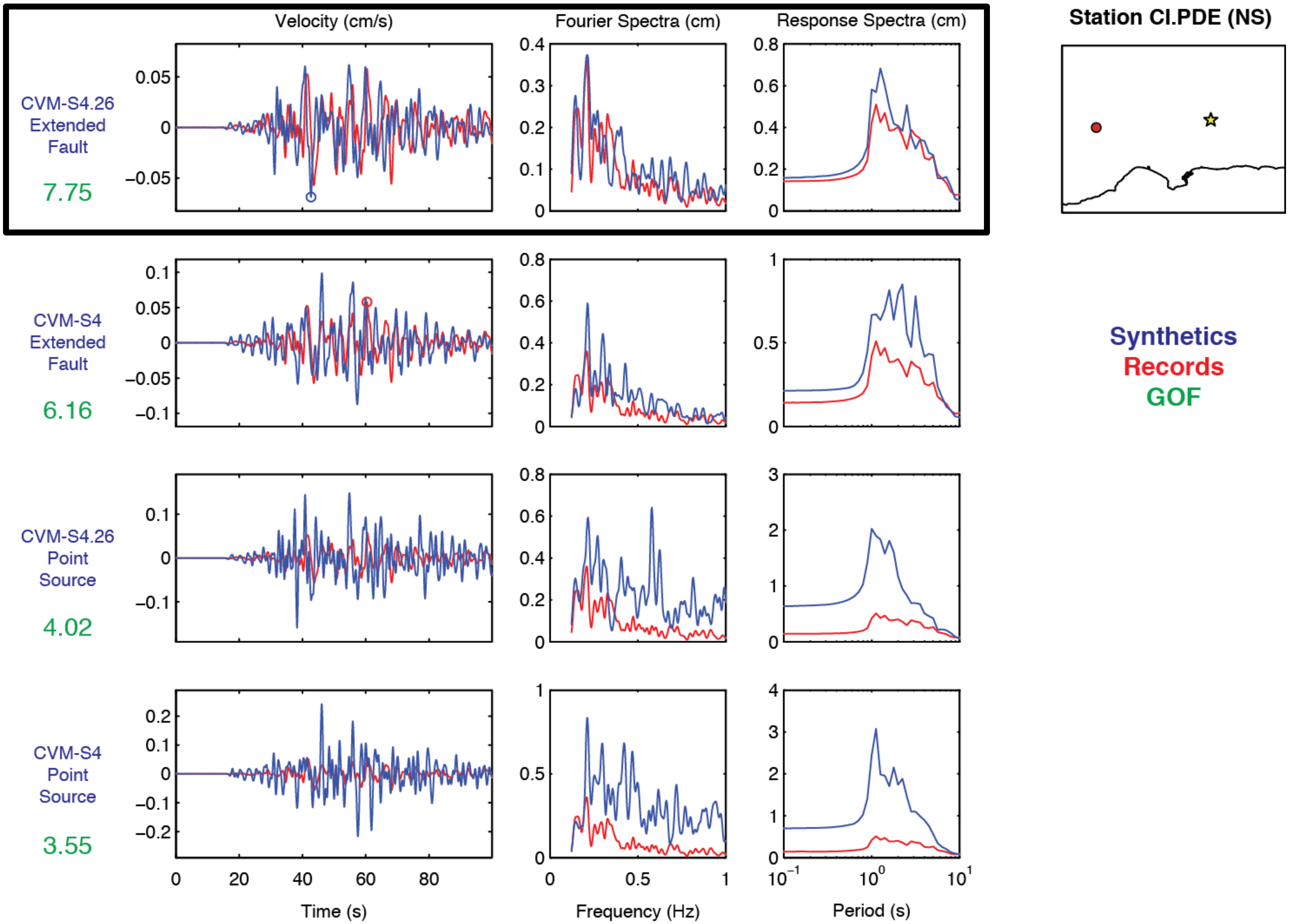
03/18/14 La Habra Earthquake (M5.1)

Southern California Earthquake Center

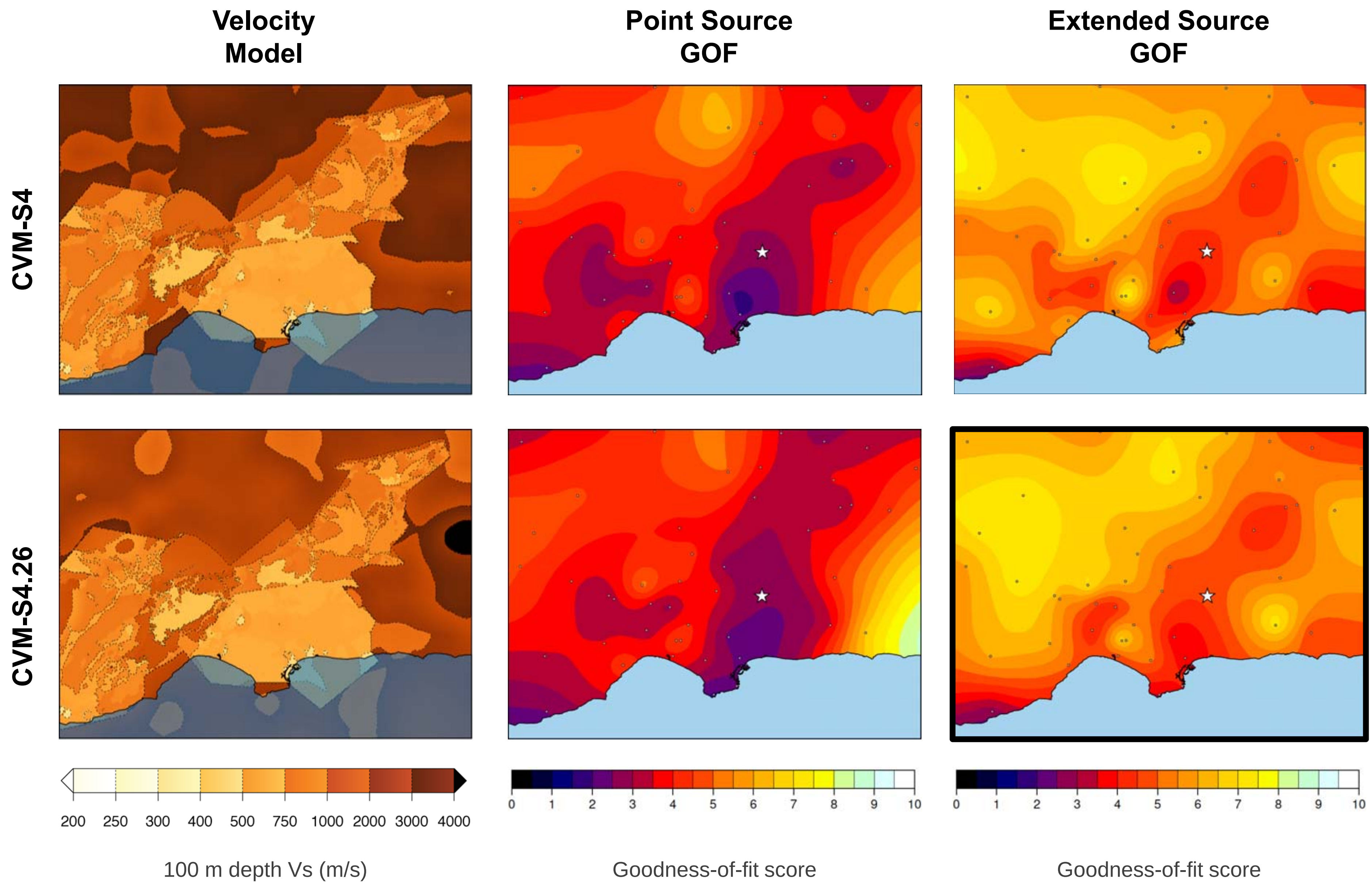


03/18/14 La Habra Earthquake (M5.1)

Southern California
Earthquake Center



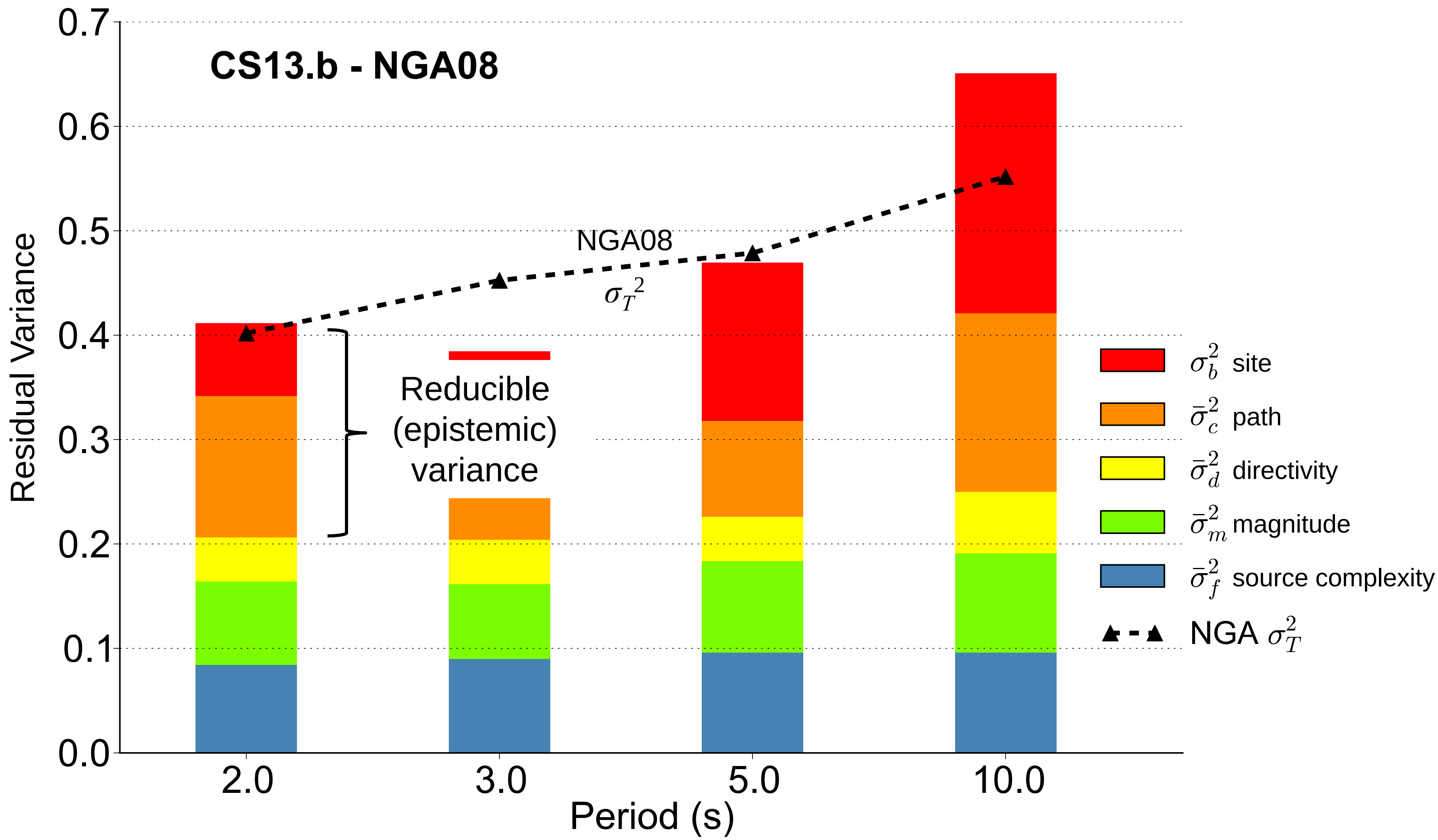
03/18/14 La Habra Earthquake (M5.1)



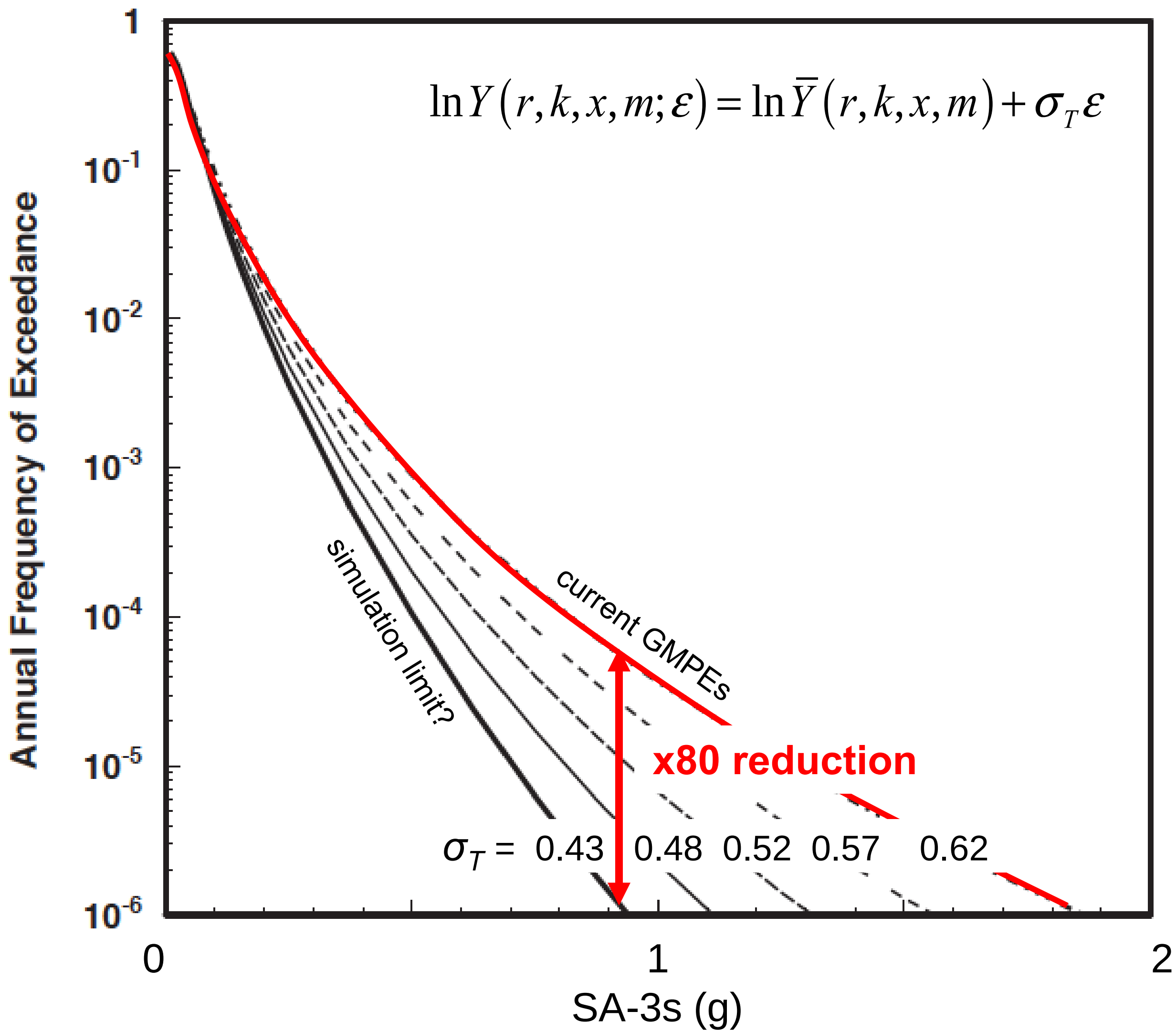
Conclusions

- **Full-scale 3D simulations of large earthquakes have been run on *Titan* at seismic frequencies up to f = 8 Hz**
  - **AWP-ODC-GPU code has achieved sustained speeds of 2.3 Pflop/s**
- **Simulation codes have been developed to model new physical aspects of high-frequency wave excitation and propagation:**
  - ***Source effects*: rough-fault ruptures and near-source plasticity**
  - ***Propagation effects*: frequency-dependent attenuation**
  - ***Site effects*: near-surface heterogeneities and nonlinearities**
- **Simulations have been validated against data and GMPEs at f > 1 Hz**
  - **CVM-S4.26 accurately predicts low-frequency waveforms**
  - **Near-source and near-surface plasticity reduces strong-motion amplitudes**
  - **Frequency-dependent attenuation of the form $Q \sim f^{\gamma}$, where γ = 0.6-0.8, fits the amplitude decay with distance for f > 1 Hz**
  - **Rough-fault ruptures and near-surface heterogeneities increase wavefield complexity, consistent with the observed spatial decorrelation of strong motions**
- **We are now extending the CyberShake hazard model to higher frequencies**
  - **First 1-Hz CyberShake simulations have been computed on *Titan***

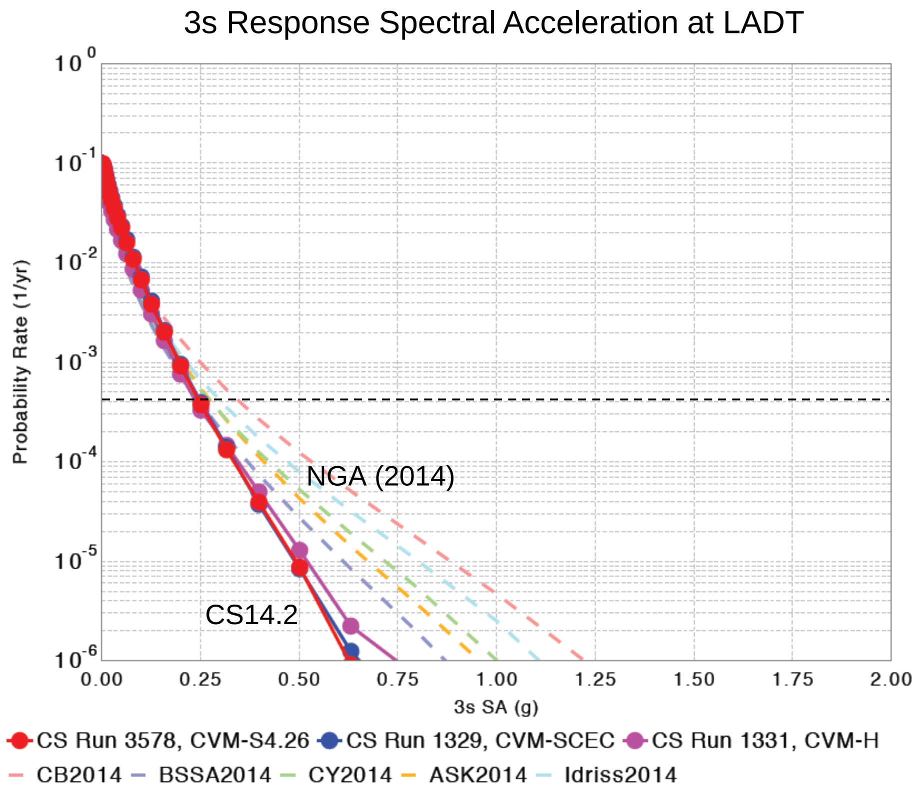
Variance Analysis of CyberShake Residuals Using Averaging-Based Factorization



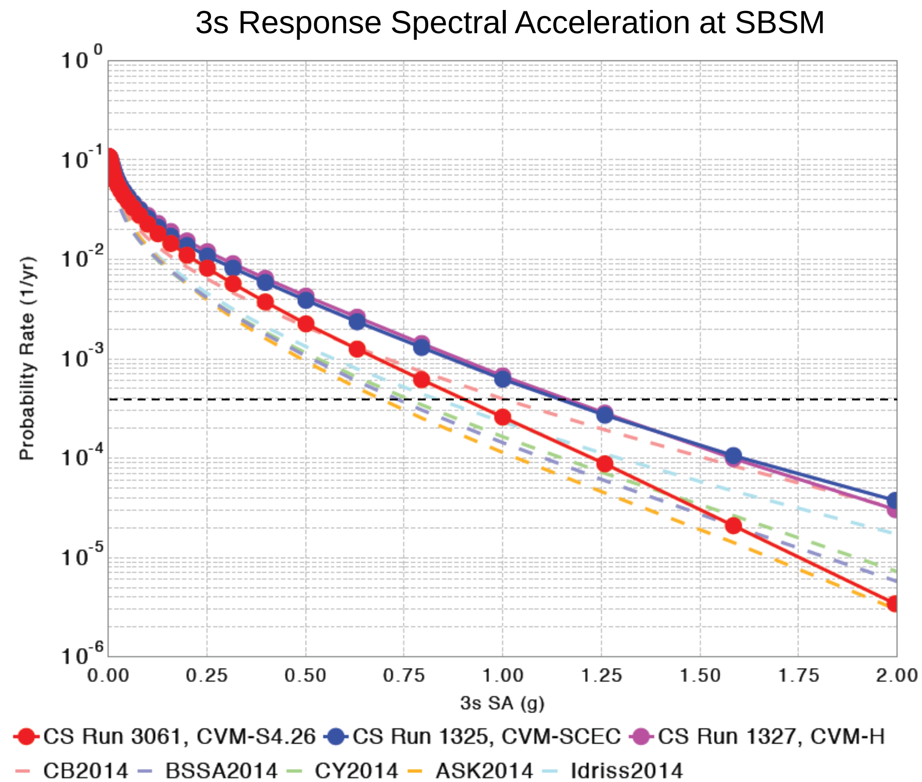
Importance of Reducing Aleatory Variability



NGA(2014)-CyberShake Hazard Curve Comparisons



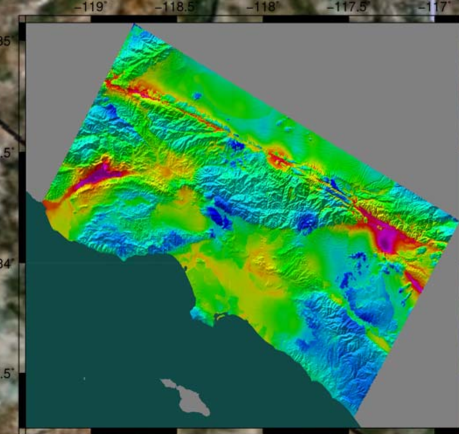
Site LADT
(Los Angeles Downtown)



Site SBSM
(San Bernardino)

Statewide CyberShake Hazard Model

Computational requirements for 1400 sites across California



***SCEC CS14.2 study on Blue Waters (Feb 2014),* 0.5 Hz deterministic, 2 components**

- **Turnaround: 342 hours**
- **XE6/XK7 nodes: 1620 (49,280 cores)**
- **Jobs submitted: 31,463**
- **Number of tasks: 470 M**
- **Storage: 57 TB**
- **Allocation hours: 16 M (CPUs + GPUs)**

***2014 CS study on Titan,* 1.0 Hz deterministic,3 components**

- **Turnaround: 2 days**
- **XK7 nodes: 13,500**
- **Sustained PFLOP/s: 2.07**
- **Jobs submitted: 34,263**
- **Number of tasks: 575 M**
- **Storage: 2 PB**
- **Allocation hours: 20 M (GPUs) + 220 M (CPUs)**

***2015 CS study on Titan,* 1.5 Hz deterministic + 10 Hz stochastic, 3 components**

- **Turnaround: 16 days**
- **XK7 nodes: 17,400**
- **Sustained PFLOP: 2.67**
- **Jobs submitted: 51,000**
- **Number of tasks: 1.73 B**
- **Storage: 8 PB**
- **Allocation hours: 160 M (GPUs) + free CPUs**

The statewide CyberShake hazard model will comprise 1.8 billion seismograms

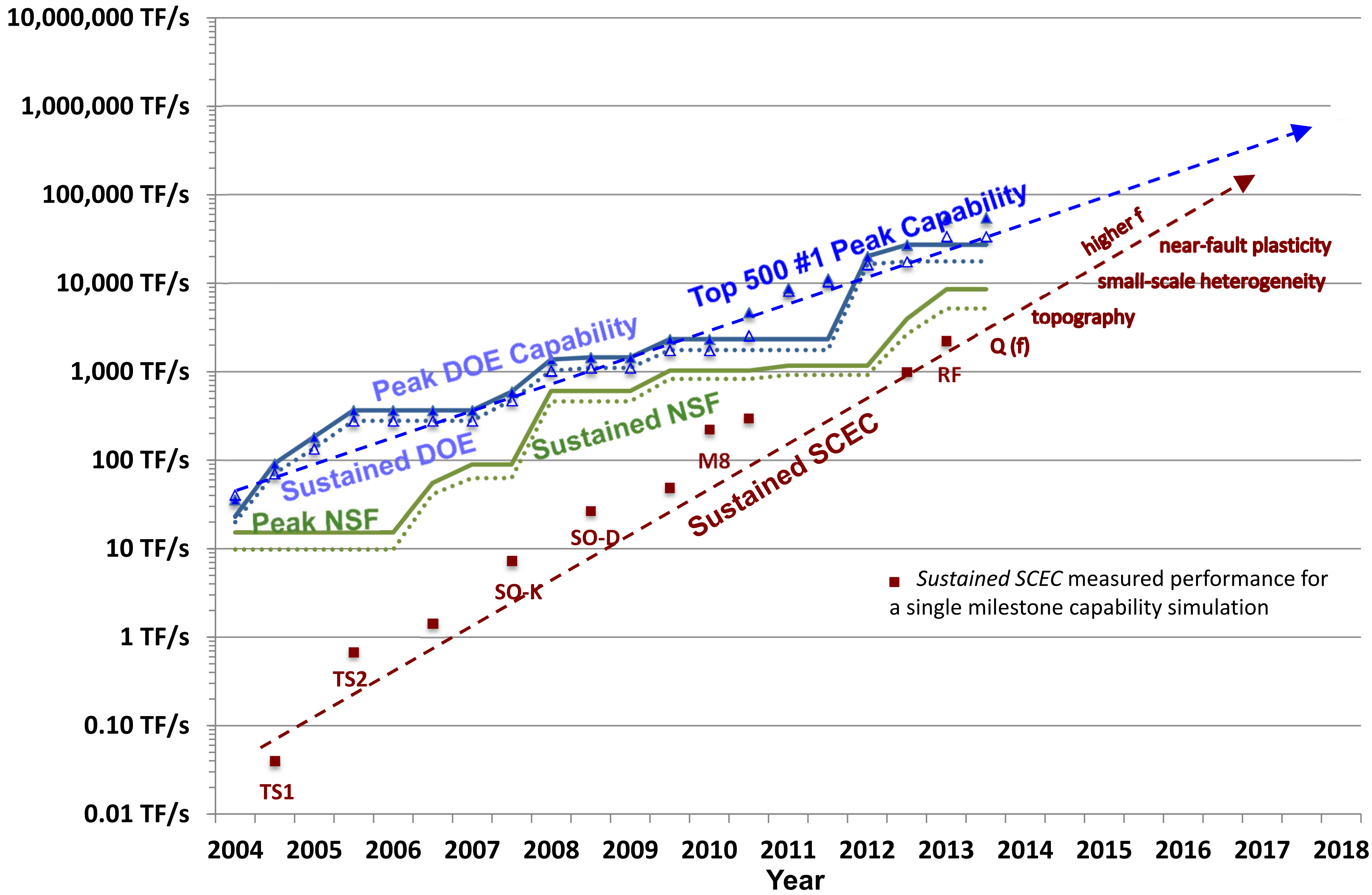
SCEC Computational Requirements

Expressed as outer/inner scale ratio at fixed time-to-solution

Table 1. The outer/inner scale ratio (in blue) of SCEC computational requirements for HPC runs

Platform	Current	Intermediate	Target	Solution Span
High-F	4-Hz Chino Hills 100K steps **1.2×10^{18}**	4-Hz ShakeOut 200K steps **3.0×10^{19}**	8-Hz ShakeOut 400K steps **4.8×10^{20}**	< 24 hrs
CyberShake	0.5-Hz 20K steps, 2,300 runs. **5.61×10^{16}**	1-Hz 40K steps, 4,200 runs. **1.65×10^{18}**	2-Hz 80K steps, 4,200 runs. **2.64×10^{19}**	< 2 weeks
DynaShake	20 m along-fault 30K steps, 20 runs **1.1×10^{16}**	2.5 m along-fault 100K steps, 100 runs **2.0×10^{19}**	1.0 m along-fault 350K steps, 50 runs **5.0×10^{20}**	< 24 hrs
F3DT	0.2-Hz, SoCal data 6K steps,17K runs **1.7×10^{16}**	1-Hz, AllCal data 57K steps, 35K runs **5.2×10^{19}**	2-Hz, AllCal data 113K steps, 35K runs **8.1×10^{20}**	< 9 days

SCEC needs extreme-scale computing…



Conclusions

- **Much of the aleatory variability in the forecasting of earthquake ground motions is due to 3D variations in crustal structure**
  - **Observed variability can be modeled by simulating seismic wave propagation through realistic 3D structures**
- **Large ensembles of simulations are needed for physics-based PSHA**
  - **Now feasible using seismic reciprocity, highly optimized anelastic wave propagation codes, and automated workflow management systems**
- **Frequency range of earthquake simulations has been extended above 1 Hz on *Titan***
  - **Models now include rough-fault ruptures, near-source plasticity, frequency-dependent attenuation, near-surface heterogeneities, and near-surface nonlinearities**
  - **Models are being validated against available earthquake data and GMPEs**
- **More accurate earthquake simulations have the potential for reducing the residual variance of the ground motion predictions by ~2x**
  - **Will lower exceedance probabilities by >10x at high hazard levels**
  - **Practical ramifications for risk-reduction strategies are substantial**

Thank you!

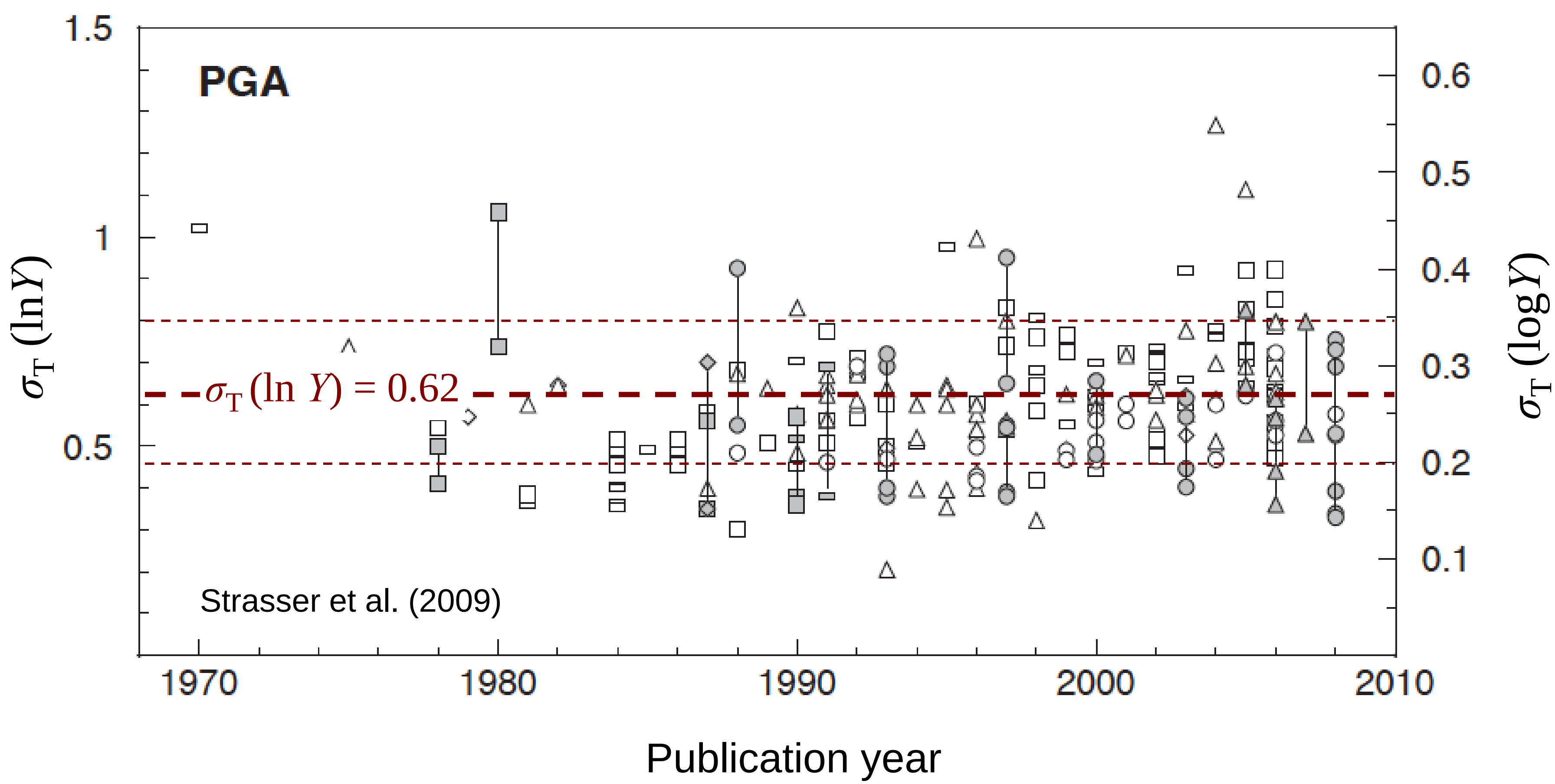
SCEC INCITE Goals & Accomplishments

1. **Develop and optimize GPU-based high performance wave propagation codes**
    - Used Titan to improve AWP-GPU code I/O capabilities to support large-scale earthquake simulations (Y. Cui, K. Olsen)
    - Used Titan to improve scalability of Hercules-GPU code improvements (P. Small, R. Taborda)
2. **Improve CVMs used in 3D wave propagation**
    - Used Mira to develop CVM-S4.26 using full 3D tomography (P. Chen, E. Lee)
3. **Create input velocity models for use in wave propagation simulations**
    - Used Titan to create Hercules eTree velocity model based on BBP 1D model using UCVM (D. Gill, R. Taborda, P. Small)
4. **Validate wave propagation models and codes by comparison to observations**
    - Used Titan to simulated La Habra 1Hz (Hercules) using a point source, and a Broadband Platform generated extended source, using CVM-S4 and CVM-S4.26 (R. Taborda, P. Small, J. Bielak)
5. **Investigate impact of 3D models in broadband simulations**
    - Used Titan to simulated Chino Hills 1Hz using a broadband platform using a point source, an extended source, with BBP 1D model and with CVM-S4.26 model and integrated low frequency seismograms into BBP validation tests. (R. Taborda, P. Small, F. Silva, D. Gill)
6. **Investigate high frequency simulations in simple velocity models**
    - Used Kraken to simulate rough fault dynamic rupture (S. Shi, K. Olsen, S. Day)
    - Used Titan to simulated 10Hz wave propagation with 1D model with and without small scale heterogeneities (Y. Cui, K. Olsen)
7. **Investigate ground motion attenuation at high frequencies**
    - Used Titan to run Chino Hills simulation up to 5Hz with alternative velocity models and attenuation models (K. Olsen, K. Withers)
8. **Calculate 1Hz probabilistic seismic hazard curves using Titan**
    - Used Titan to Integrate CVM-S4.26, UCVM, and AWP-GPU codes to perform our first 1Hz CyberShake PSHA hazard calculations. (S. Callaghan, Y. Cui, R. Graves, K. Olsen, D. Gill, E. Poyraz)

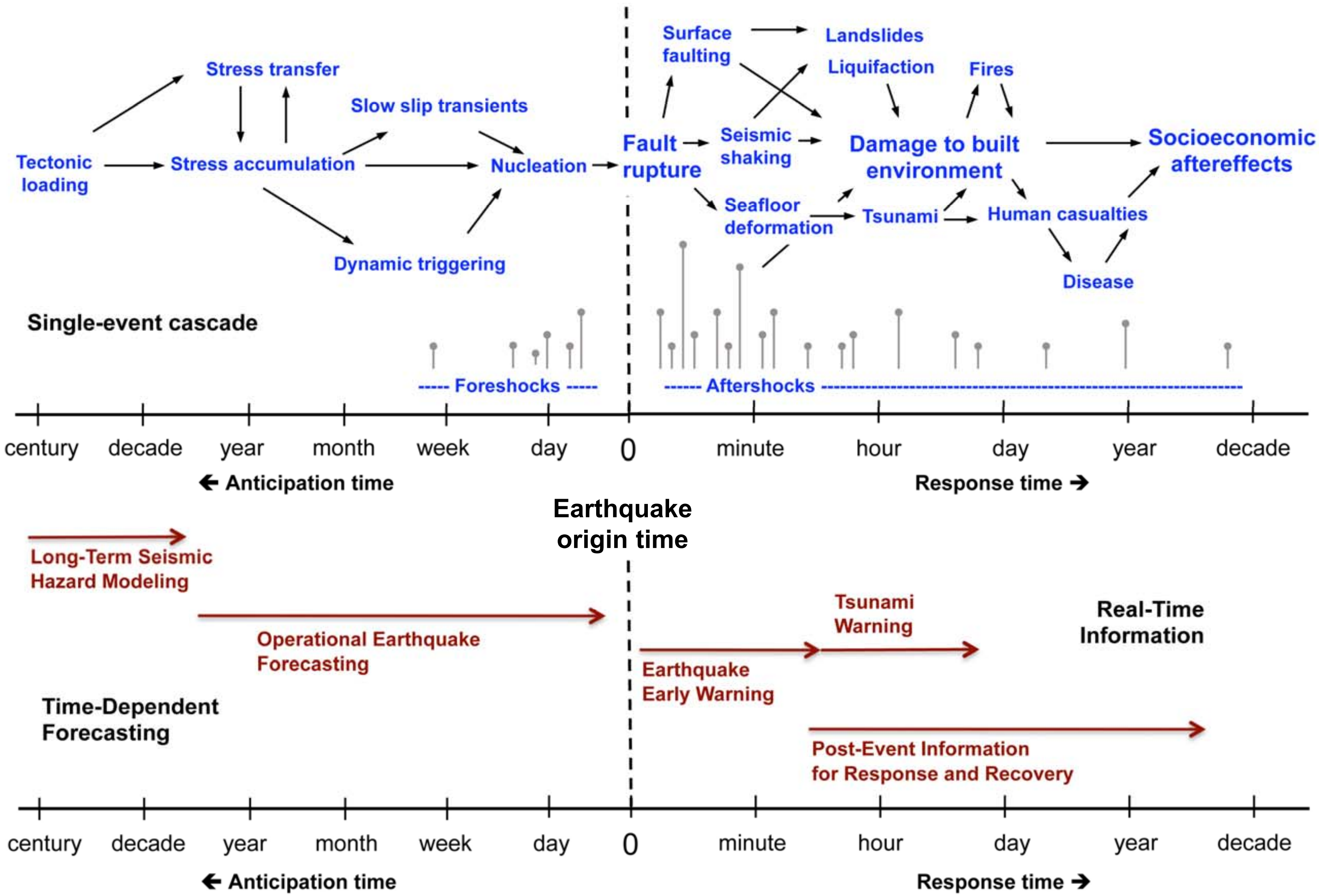
SCEC Computational Plan 2015-2016

	Research and Activity Area	Science Lead	Milestone Description	Code	# of Sim	SU/Sim (mill.)	Titan Sus (mill.)	Titan Data (TB)	Mira Sus (Mill.)	Mira Data (TB)
G1	Tomography Velocity Models	Chen	0.2 Hz regional inversions for southern and northern California velocity models	AWP-ODC	20	2.40			48.00	129.00
G2	Material Heterogeneities Wave Propagation	Olsen	2 Hz regional simulations for CVM with small-scale stochastic material perturbations	AWP-ODC-GPU	8	1.60	12.80	120.00		
G3	Structural representation and wave propagation	Bielak, Taborda	4 Hz scenario and validation simulations. Use of different velocity models and attenuation (Q) models, including frequency dependent Q and near surface nonlinear behavior.	Hercules-GPU	10	0.75	7.50	6.00		
G4	CyberShake PSHA	Jordan	1.0Hz CyberShake Hazard map at 1.0Hz 500m/s Min Vs, output 3 components using 10 billion elements, 40k timesteps	AWP-ODC-GPU	300	0.33	99.00	10.00		
Year 1 Totals							119.30	136.00	48.00	129.00
G5	Tomography Velocity Models	Chen	0.5 Hz regional inversions for southern and northern California velocity models	AWP-ODC	5	19.00			95.00	441.00
G6	Attenuation and Source Wave Propagation	Olsen, Day	10 Hz simulations integrating rupture dynamic results and wave propagation simulator	AWP-ODC-GPU	5	3.80	19.00	190.00		
G7	Structural representation and wave propagation	Taborda, Bielak	8 Hz scenario and validation simulations. Integration of frequency dependent Q, topography, and nonlinear wave propagation	Hercules-GPU	5	10.00	20.00	5.00		
G8	CyberShake PSHA	Jordan	1.5 Hz CyberShake Hazard map with 250 m/s Min Vs, output 3 components using 83.3 billion elements, 80K timesteps	AWP-ODC-GPU	200	0.66	132.00	15.00		
Year 2							171.00	210.00	95.00	441.00
Two year							290.3	346.0	143.0	570.0

Persistence of σ_T in Empirical GMPE Studies



Prediction Problems of Earthquake System Science



Prediction Problems of Earthquake System Science