The Future of Ground Motion Simulation: Harnessing the Power of High-Performance Computing

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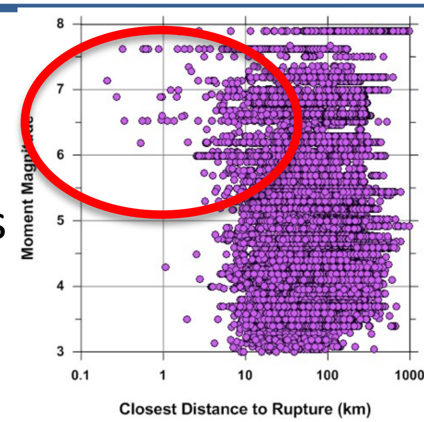
- Norm Abrahamson (UCB & UCD)
- Albert Kottke (PG&E)
- **Computing Facilities**
  - NERSC (LBNL)
  - Livermore Computing (LLNL)

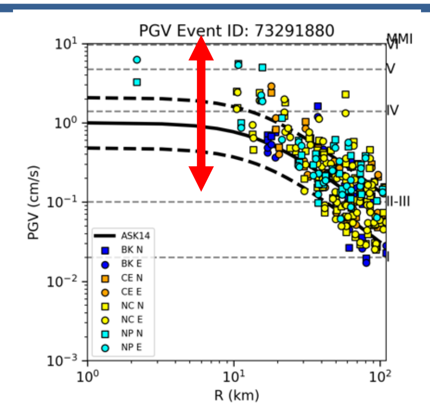
Outline

- Motivation
- The GM simulation methods
  - 1D, 3D, deterministic, stochastic, kinematic, dynamic
  - High-Performance Computing is needed for realistic simulations
- Challenges for more realistic and useful GM simulations
  - Computational – Efficiency, porting to emerging HPC resources
  - Physical
    - Source – need realistic source models to represent excitation of seismic waves
    - Path – 3D Earth models must represent crustal structure across length-scales
    - Site – capture 3D effects, body and surface waves, variability
- New results for M_W 7.0 Hayward Fault ruptures

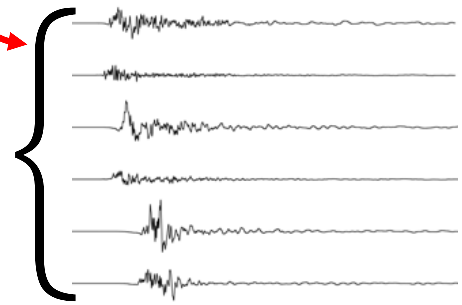
Simulations provide valuable constraints on site-specific near-fault ground motions

- Empirical data are limited
  - Few observations at short distance
  - Variability due to different regions, conditions



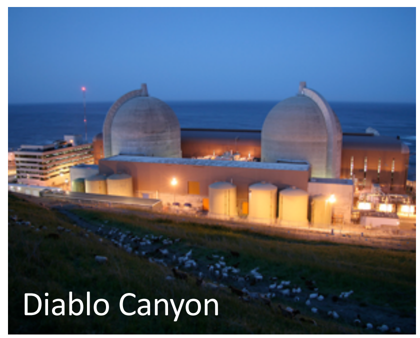


- Near-fault motions are highly variable
  - Motions shaped by rupture details
    - Slip, directivity, rise-time, rupture speed
    - Displacement step and velocity pulse
    - Coupling into sedimentary basins



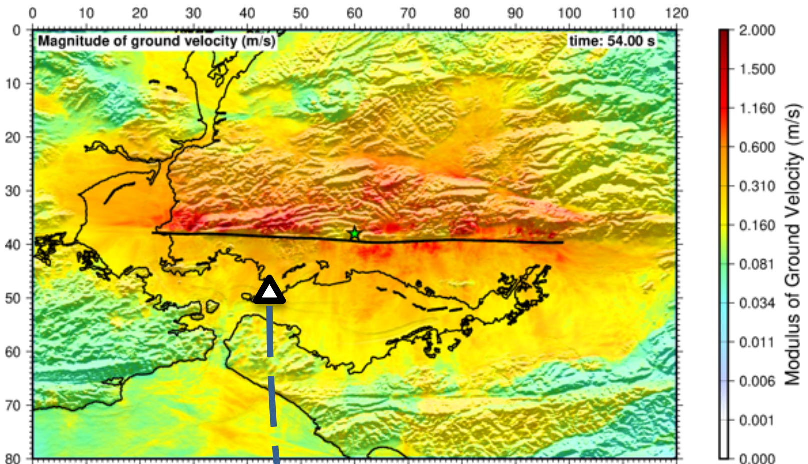
- Hazard to structures by specific faults, deterministic scenarios
  - Critical facilities (e.g. nuclear installations)
  - Transportation infrastructure
  - Lifelines (electricity, water, gas)


Caldecott Tunnel

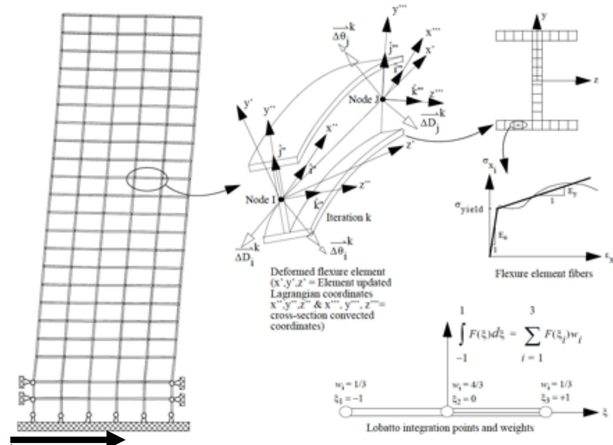

Diablo Canyon

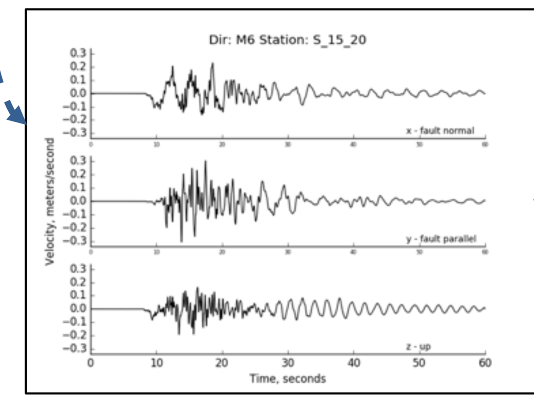

Electric Grid

Computed motions support engineering applications: geotechnical, building and/or SSI response

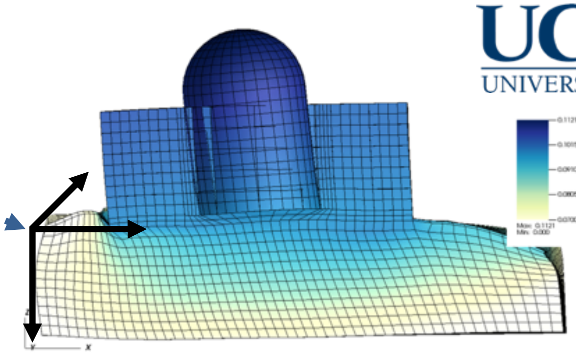


NEVADA: Building response





ESSI: Soil-structure response



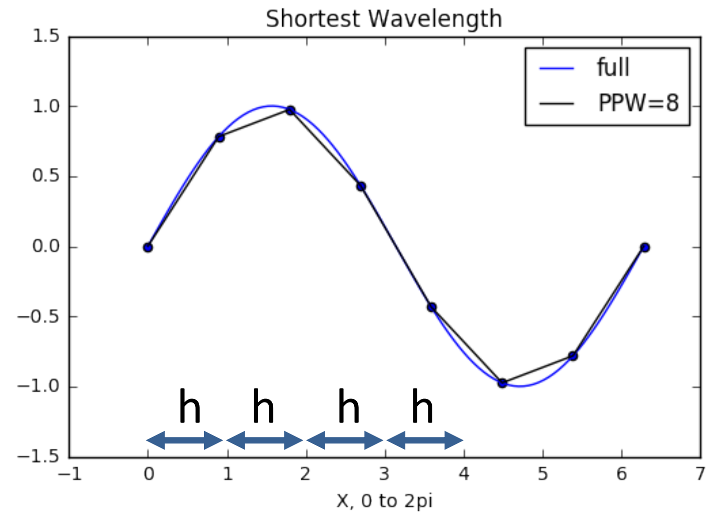
See Dave McCallen's talk Friday afternoon

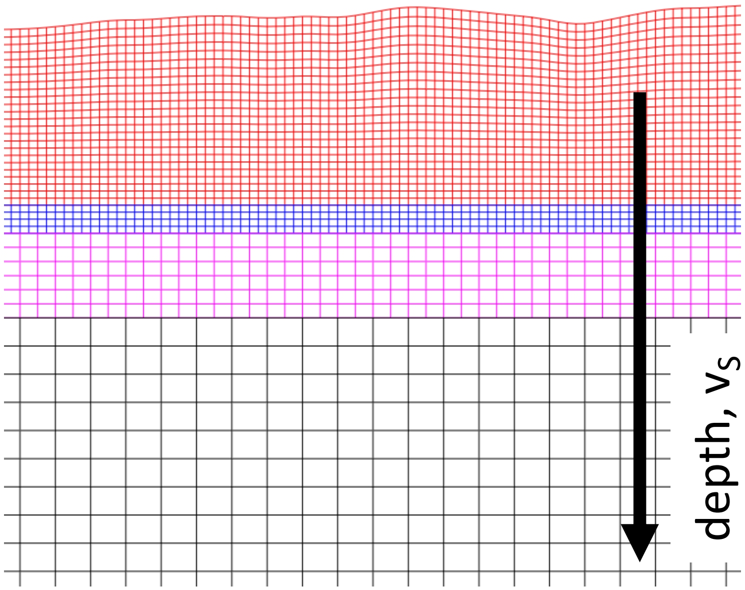
Ground Motion Simulation Methods

Method	Source	Advantages	Disadvantages
Stochastic – acceleration time-history is white noise, shaped to fit response spectra	Kinematic	easiest	unrealistic spatial and spectral correlations
1D Kinematic, Anelastic – laterally homogeneous, plane-layered model, e.g. wavenumber integration	Kinematic	easy	simplified wave propagation 1D, plane-layered, no basins
Hybrid – 1D or 3D low freq, stochastic high freq (e.g. SCEC BBP, CyberShake)	Kinematic	relatively easy, modest HPC for 3D	high freq. stochastic (see above)
3D Kinematic, Anelastic – includes lateral heterogeneity, e.g. FD, FEM, SEM, DG	Kinematic	full waveform, 3D wave propagation w/ attenuation, basins	requires HPC, steep climb to increase f_{max} 16x to double freq.
3D Dynamic Rupture – fracture mechanics, friction laws, spontaneous rupture on fault	Dynamic	includes physics of fracture, generates slip time-dependence	Most comp. intensive, important unknown or poorly parameters
3D Non-Linear - Non-linear geomechanics, plasticity	K or D	More realistic for high GMs, damping	Most comp. intensive, even more unconstrained parameters …

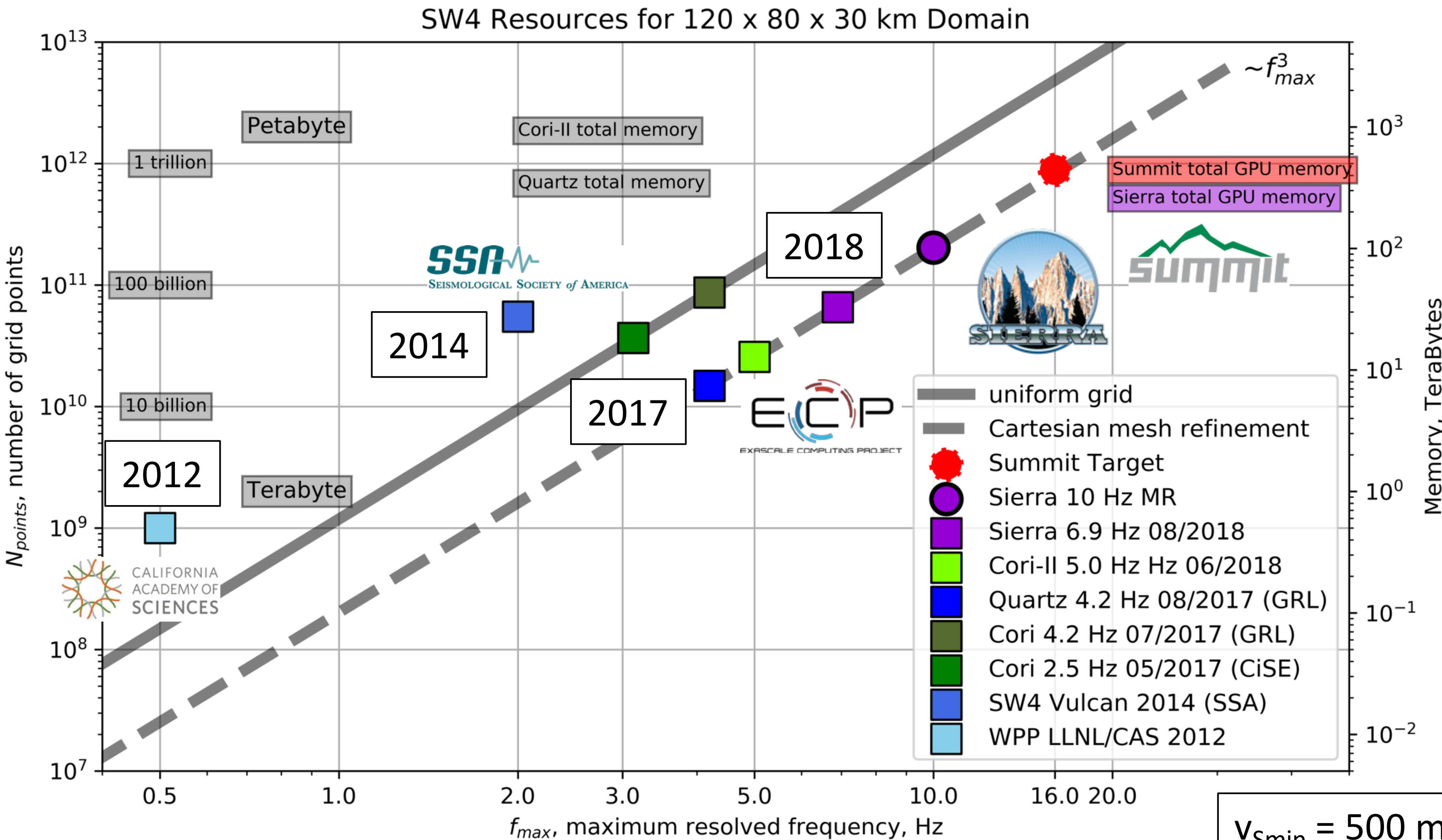
3D full waveform seismic simulation methods (FD, FEM, SEM, DG) require fine discretization

- Methods need a certain number of grid points per shortest wavelength (PPW), grid spacing = h
  - Numerical solution is more accurate as PPW increases
- Doubling the highest resolved frequency, f_{max}, generally requires:
  - 8x more grid points, 2x more time steps
  - 16x increase in computational effort
  - $f_{max} = v_{min} / (PPW * h_{min})$
- Seismic wavespeeds increase with depth, so increasing grid spacing with depth greatly improves memory and computational efficiency





Ever-increasing ease of regional-scale simulations: M_W 7.0 Hayward Fault on various machines

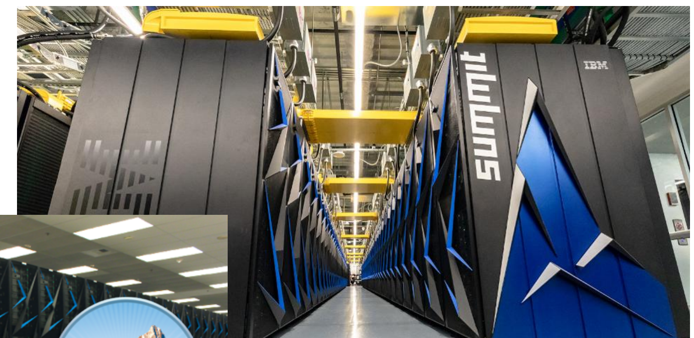


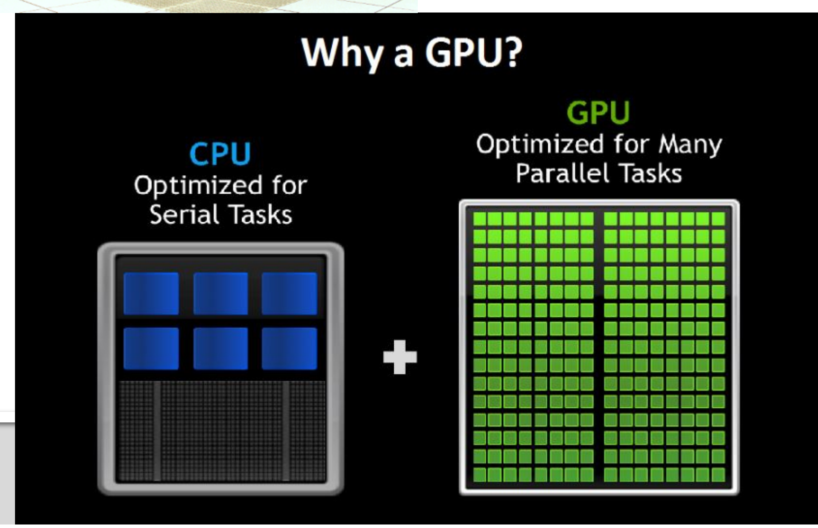
v_{Smin} = 500 m/s

Challenges: Computational efficiency

- Early HPC systems were clusters of networked CPU nodes with MPI
- Integration of many cores per node, multi-threading improved efficiency
- State-of-the-art systems rely on graphic processing units (GPU's)
- Software must be written to make use of new hardware
  - Algorithms modified and tested
  - RAJA enables efficient offloading of work from CPU to GPU

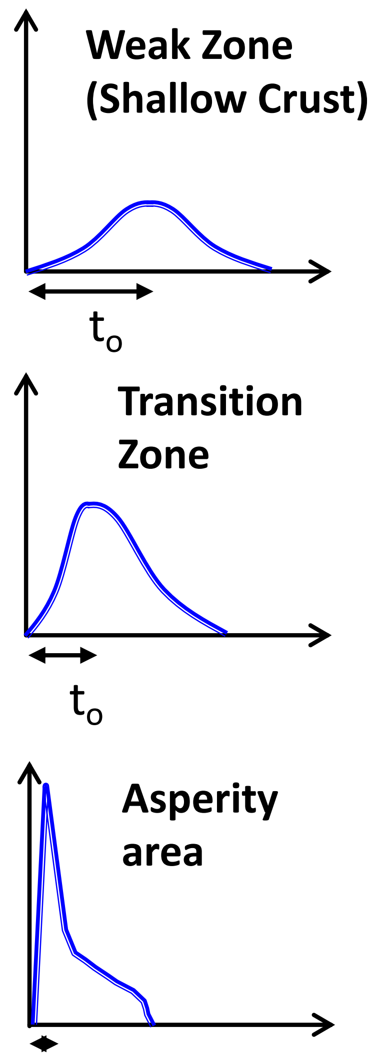
Summit & Sierra

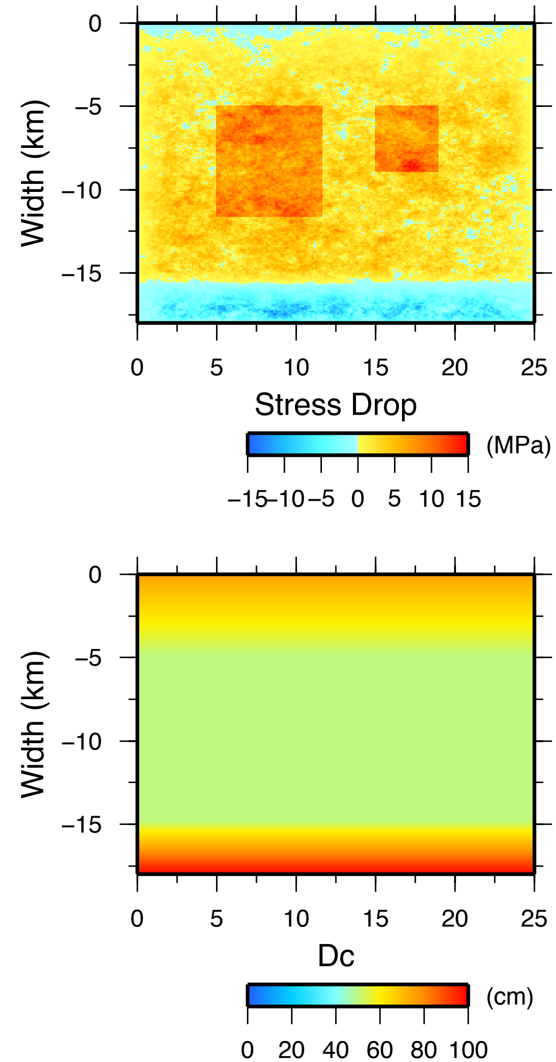




Challenges: Source modeling

- We expose details of the source rupture process as we increase the frequency content in our kinematic simulation
- Rupture dynamics informs the nature of slip
- Rock strength depends on depth
  - Rise time, t_0 ~ duration
  - Duration ~ slip
  - But, depends on depth, local rock strength

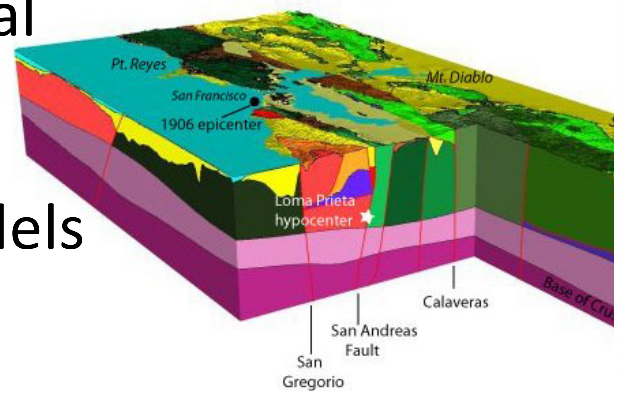




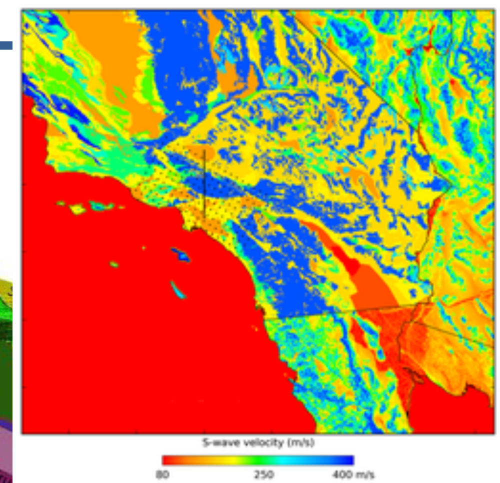
(Arben Pitarka, work in progress)

Challenges: Path, improve 3D crustal structure

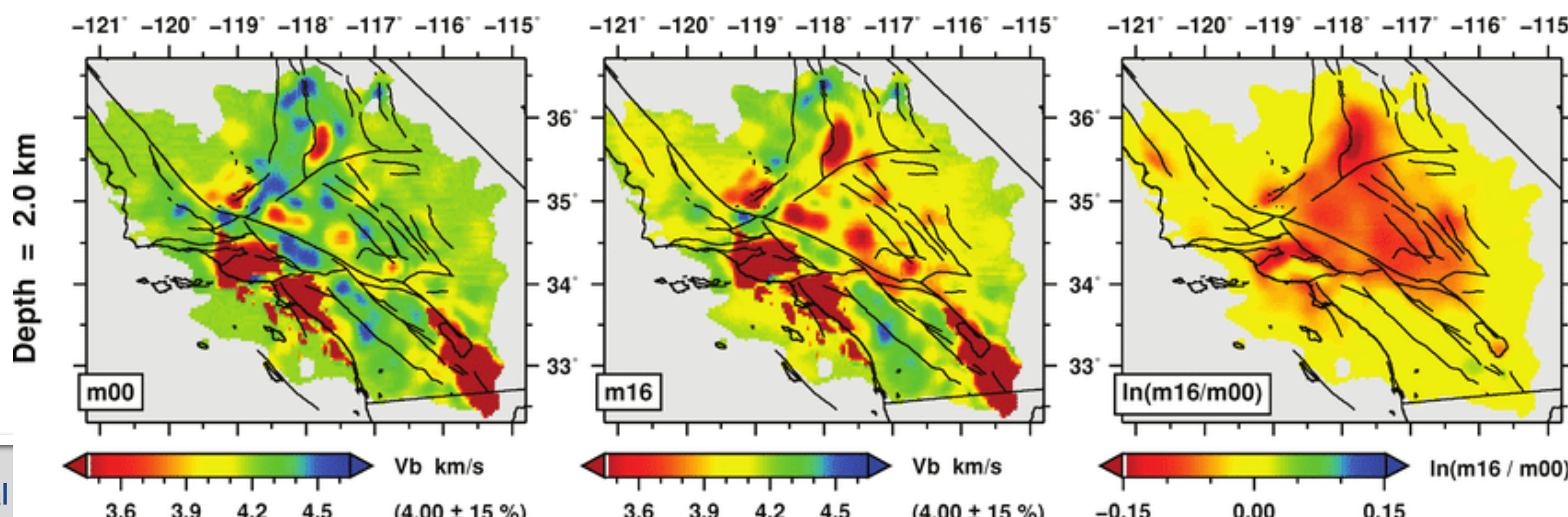
- Ad hoc models generally built based on geologic & geophysical data
- Many seismic tomography models generally don't fit waveforms
- Waveform-based inversion offers possibility to resolve crustal structure



CVM-H v6.3 + GTL



GTL surface S-wave velocity derived from Wills and Clahan (2006) geology based V_{s30} map, supplemented outside of California with Wald et al. (2007) map.

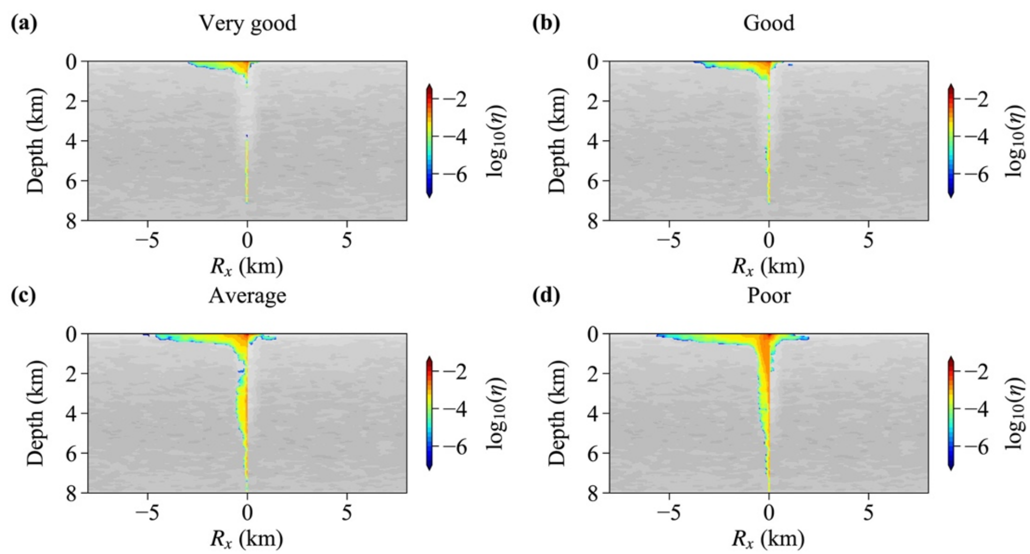


(Tape et al., 2009)

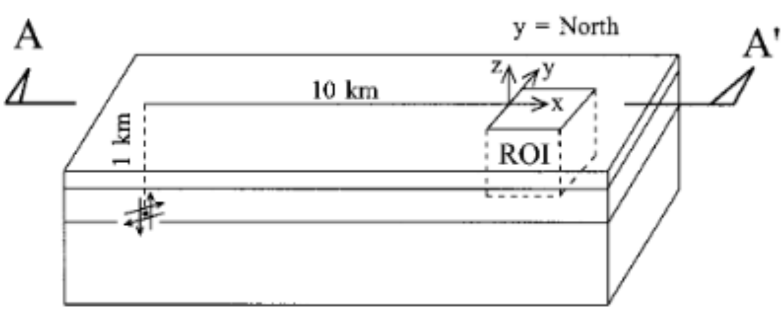
Challenges: Path & Site, improved geomechanics

- Account for mechanical response beyond linear elasticity
  - 3D plasticity
  - Models fault zone & near-surface
- Domain Reduction Method (DRM) approach
  - Geotechnical & SSI

Plastic deformation with different rock properties



(Roten et al., 2017, GRL)

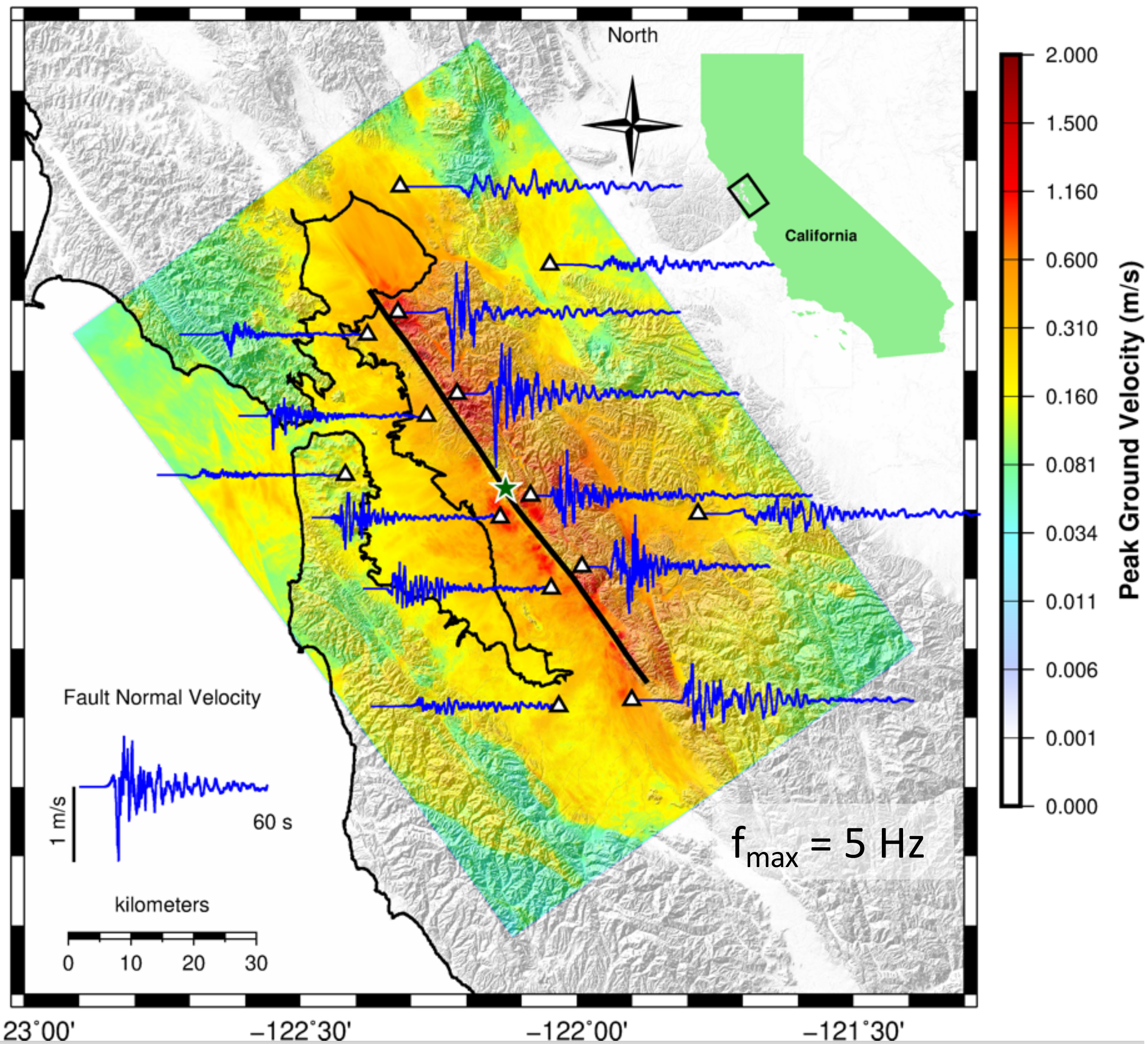


more complex

Jacobo Bielak and co-workers

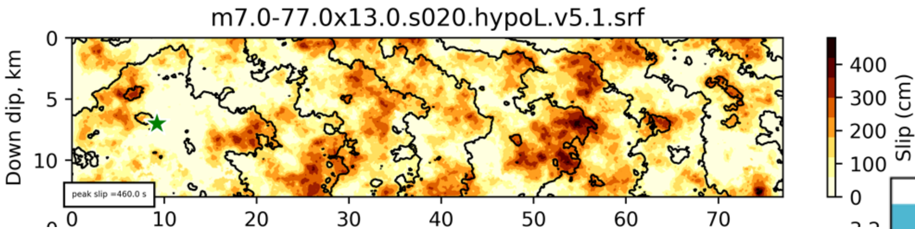
HPC ground motion simulations for Hayward Fault M_W 7.0 scenario earthquake

- SW4 FDTD simulations
- Physics-based wave propagation:
  - 3D geologic/seismic model
  - topography
  - attenuation
- Broadband, deterministic
  - f_{max}: 5 – 10 Hz
  - h_{min} = 12.5 – 6.25 m
- Run on large HPC systems
  - Port to GPU/CPU systems
- Motions for engineering analysis
- Motions agree well with GMM's

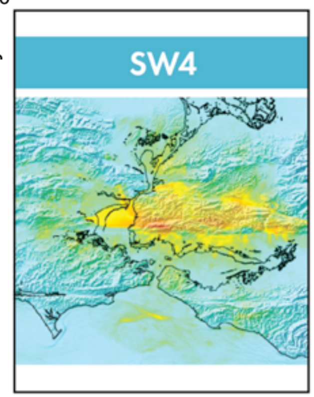


Our goal is to compute broadband motions in 3D models with purely deterministic methods & HPC

Ruptures: Graves & Pitarka (2016)



Solver



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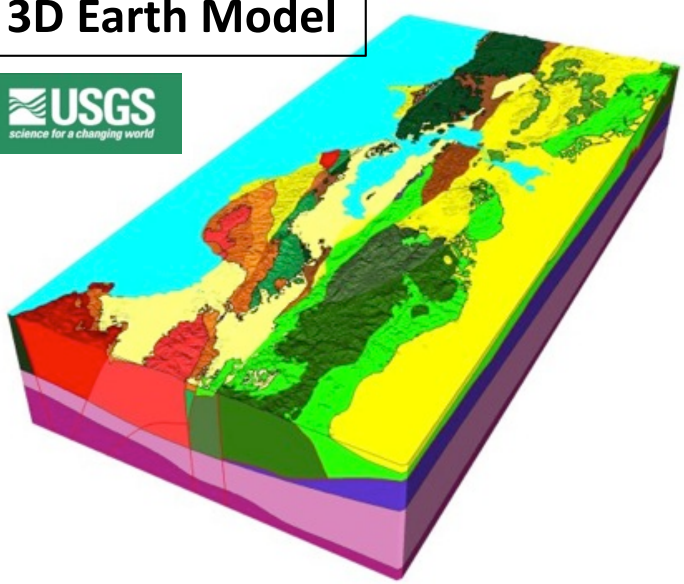
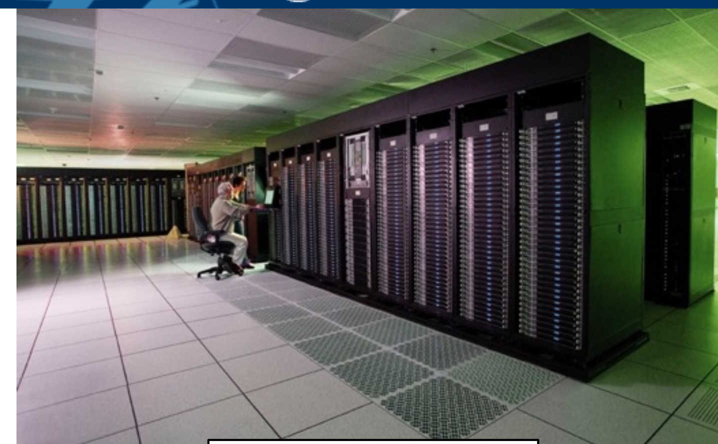
3D Earth Model

USGS science for a changing world



HIGH PERFORMANCE COMPUTING @ Lawrence Livermore National Laboratory

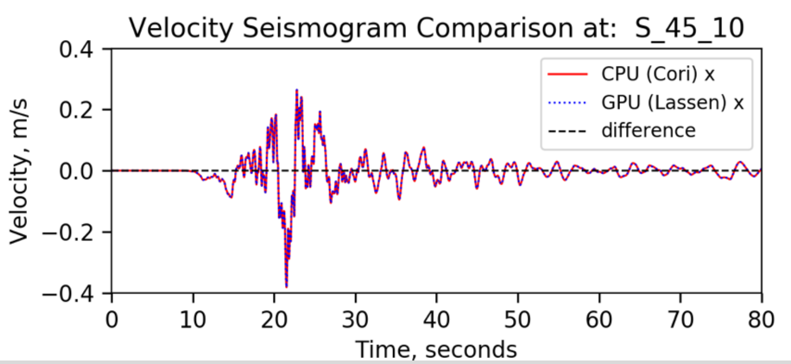


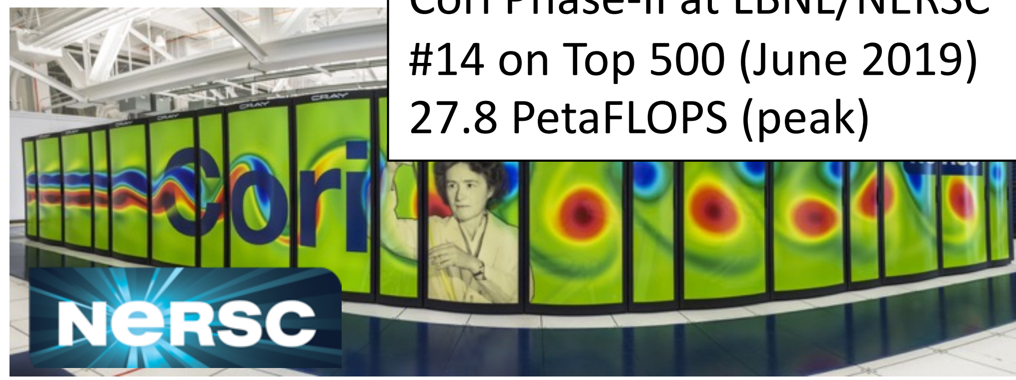
HPC Cycles

NERSC

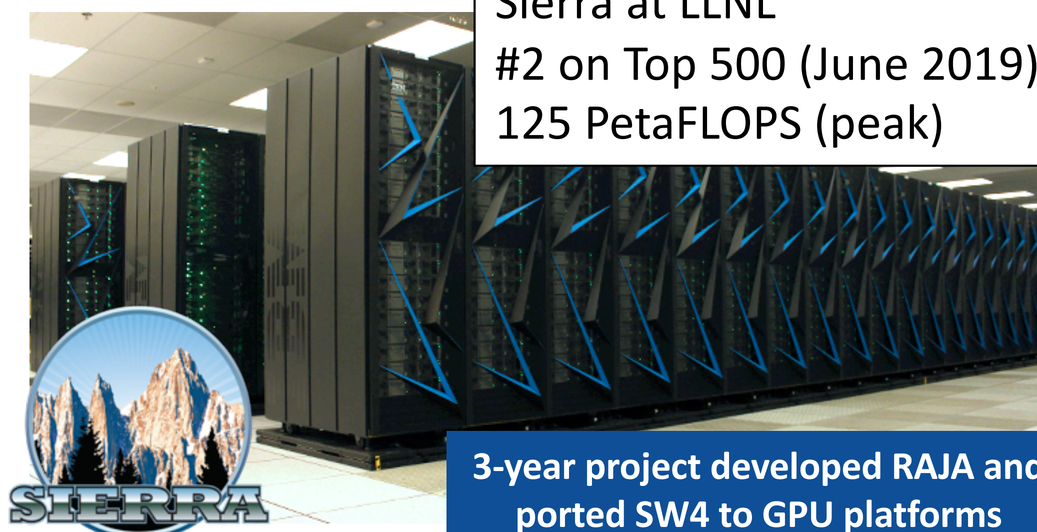
Recent developments enable SW4 simulations on the world's most powerful computers

- For 0-5 Hz HF M 7 rupture, we obtained ~50x speed-up in node-hour performance:
  - Cori: 8,192 nodes * 10 hours = 81,920 node-hours
  - Sierra: 256 nodes * 6.6 hours = 1,690 node-hours
- Verification for 0-5 Hz of SW4-RAJA (Sierra) and SW4 (Cori)





Cori Phase-II at LBNL/NERSC
#14 on Top 500 (June 2019)
27.8 PetaFLOPS (peak)



Sierra at LLNL
#2 on Top 500 (June 2019)
125 PetaFLOPS (peak)

3-year project developed RAJA and ported SW4 to GPU platforms

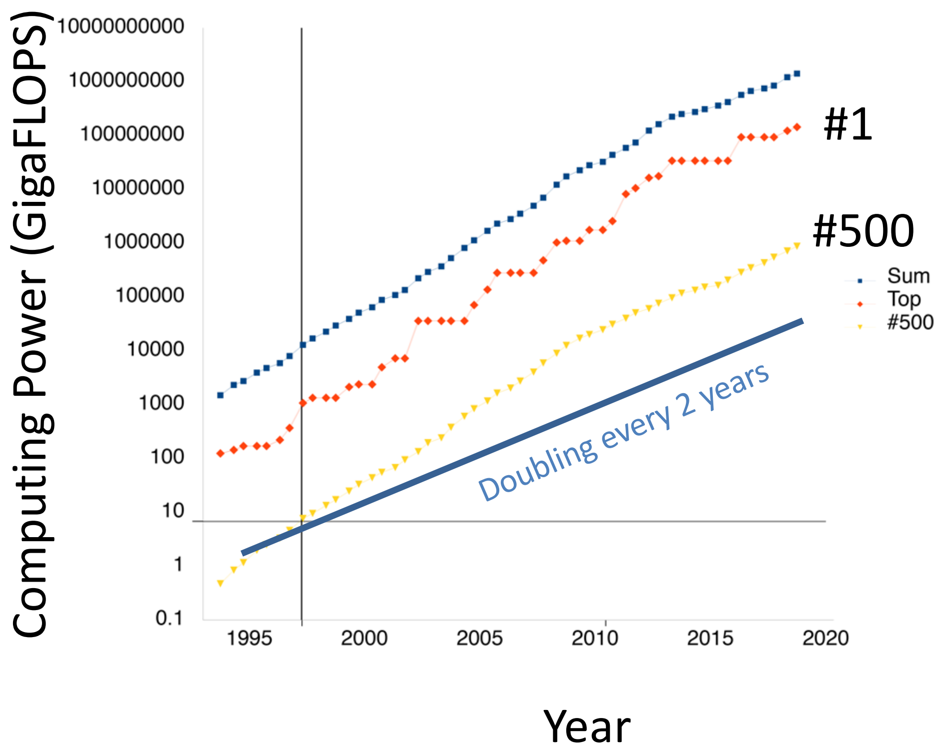
Moore's Law, the IEEE Top 500 and Earthquake Science and Engineering

Moore's Law is the observation that the number of transistors in a dense integrated circuit doubles about every two years. (Gordon Moore, 1965, Wikipedia)

- Computers keep getting more powerful
- Enabling disruption to meet challenges and break barriers in science and engineering

Technology companies anticipate growth in computational power without knowing the specifics of next generation architectures.

IEEE Top 500 Statistics (Wikipedia)



Future methods in seismic hazard and risk should rely on physics-based 3D simulations to provide ground motions for structural response and performance-based design

Summary take away points

- Three factors contribute to more accessible broadband 3D GM simulations:
  - Improvement in numerical methods & algorithms
  - Inexorable growth in computing power
  - Optimization of computer codes (programs) to run on new platforms

- Three elements require ongoing research:
  - Realism of earthquake rupture models
    - Particularly slip function & rise time as we push to higher frequencies
    - Follow developments in dynamic rupture modeling
  - Improvement in 3D crustal models
    - Particularly the upper crust (0-4 km) and smaller scale structure
    - Full waveform inversion methods promise to improve resolution
  - Methods to account for geotechnical structure
    - Particularly short-scale length heterogeneity, 2D & 3D, non-linear effects