Earthquake Simulators are Ready for Prime Time

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Earthquake Physics

- Many basic uncertainties remain

  Absolute stress levels order of magnitude uncertain

- Invariances hold hope for transcendence

  Constant stress drop from small to great earthquakes

- Candidate models exist

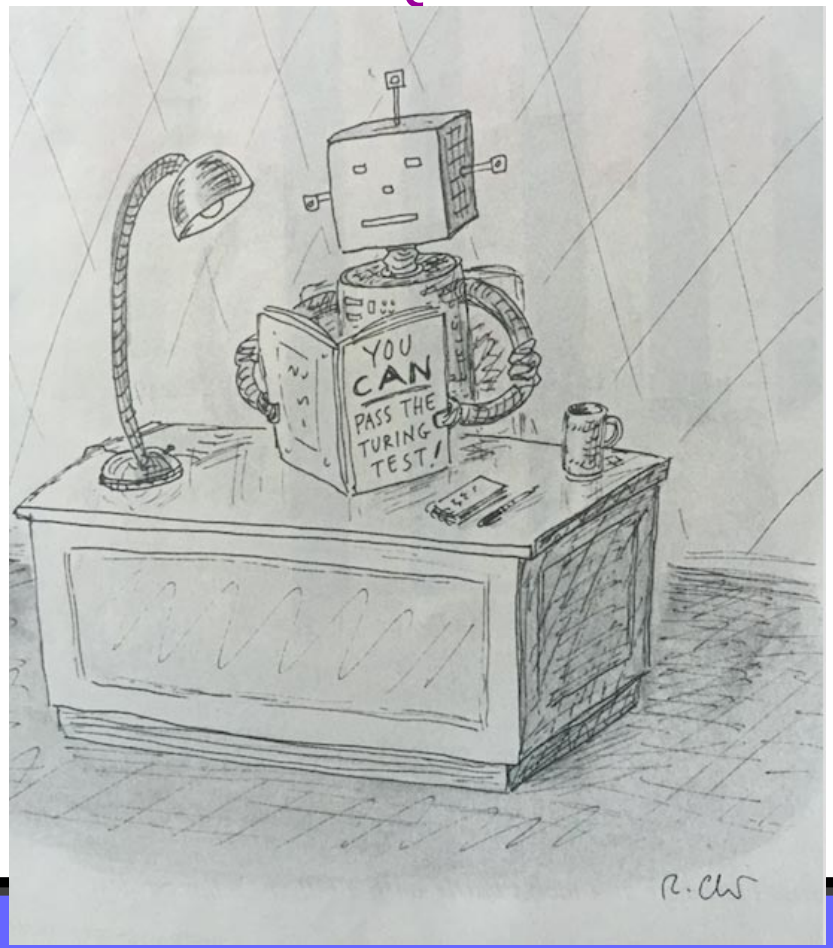
  Do candidate models look sufficiently like observations?

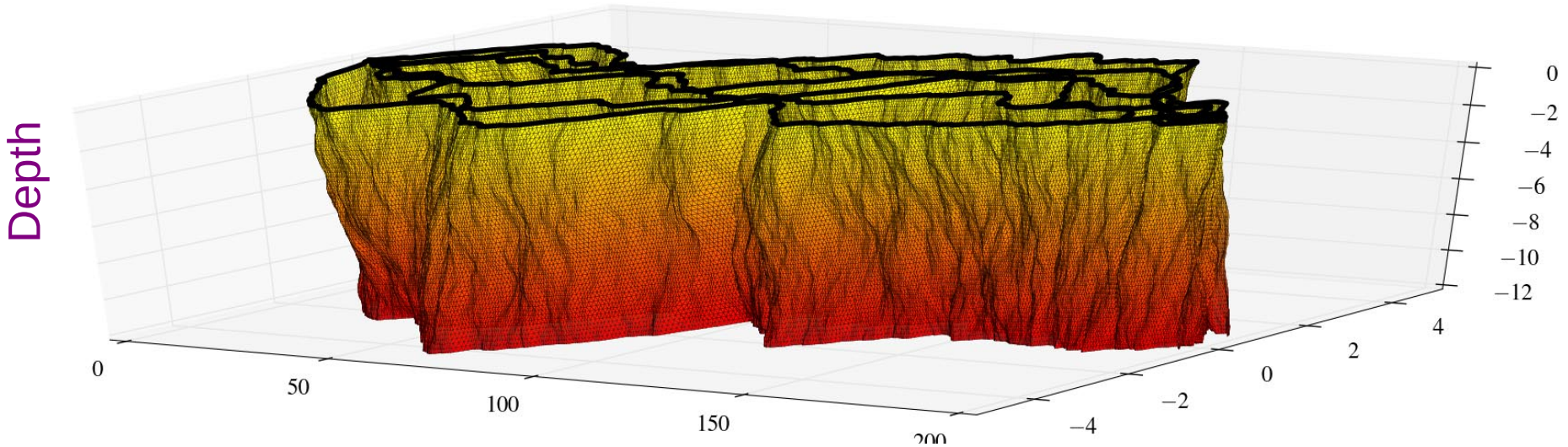
  Can models help with hazard questions?

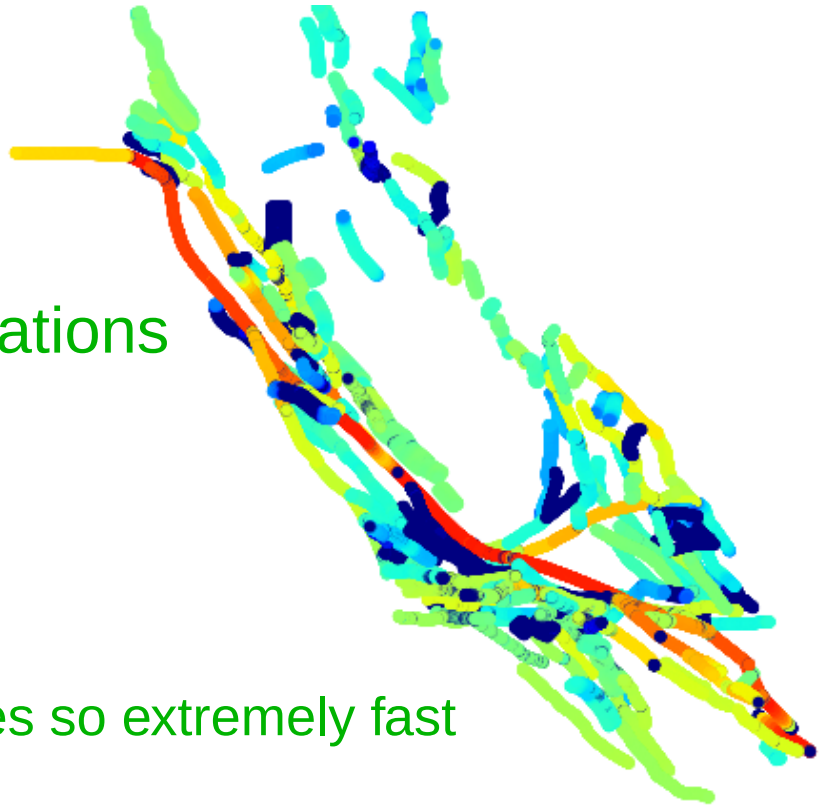
Earthquake Simulators

- Approximations to dynamics to make comptutationally tractable
- Can handle complex geometries and large scales
- Doing really well on validation gauntlet!

RSQSim



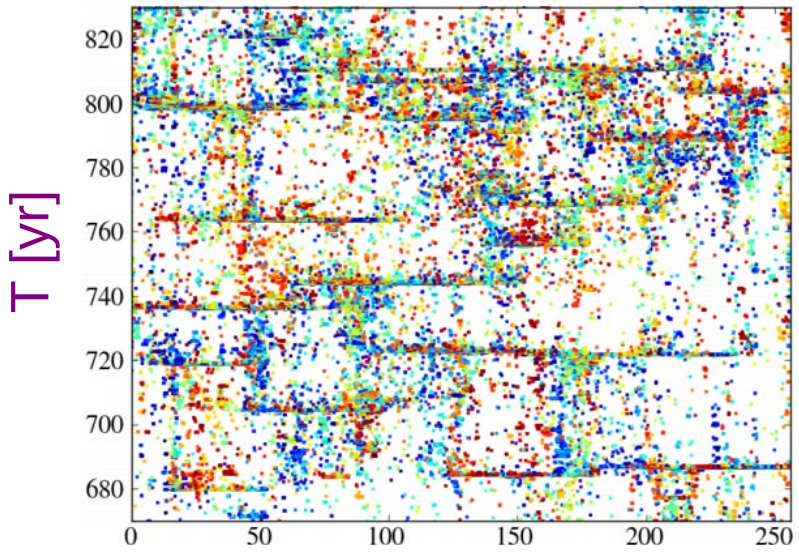


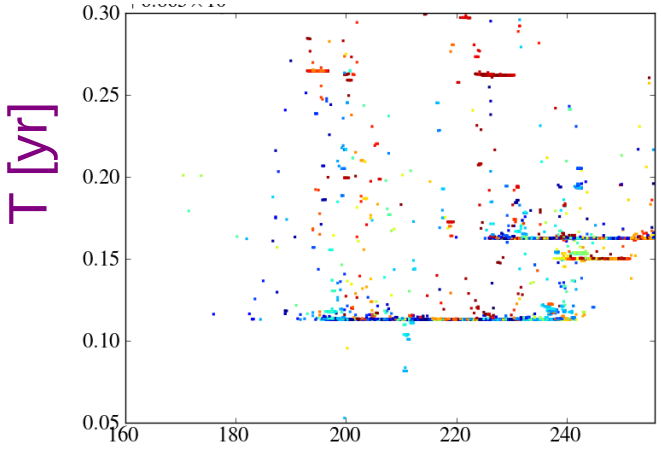


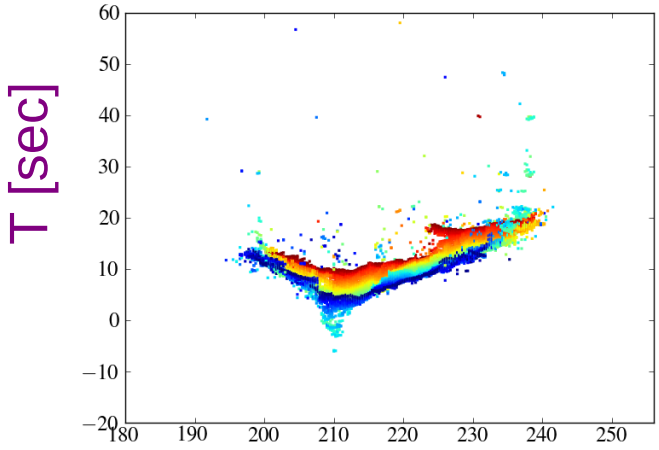
Simulator Features & Approximations

- Complex geometries
- Quasistatic boundary elements
- Rate-and-state friction
- Fixed fast sliding rate
- Time step just during state changes so extremely fast

Seismicity in Different Timescales

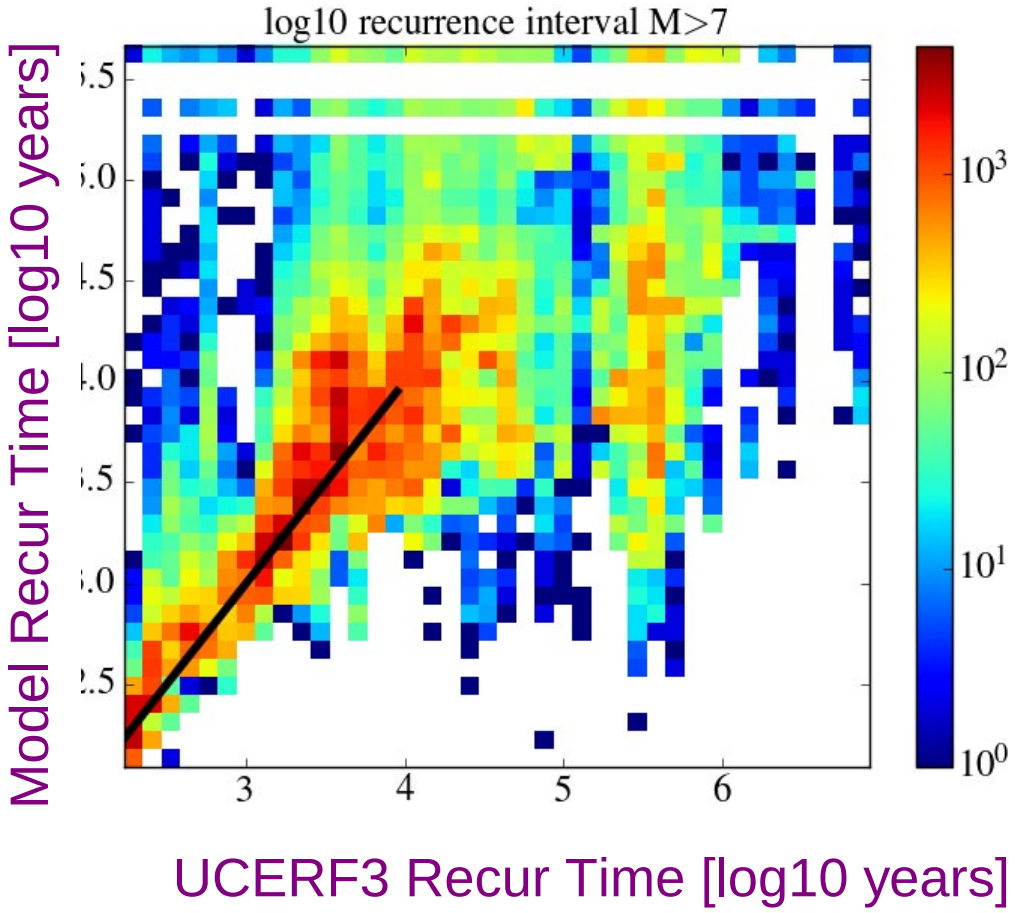






- Aftershocks along mainshock rupture area

Untuned Model Recurrence Intervals



- Untuned model did really well on recurrence intervals
- Push further into hazard comparison

Earthquake Hazard

- Can’t wait for physics uncertainties to be resolved
- Longstanding methodology developed

  Probabilistic Seismic Hazard Analysis [PSHA]

- Difficulties with PSHA

  Many uncertainties

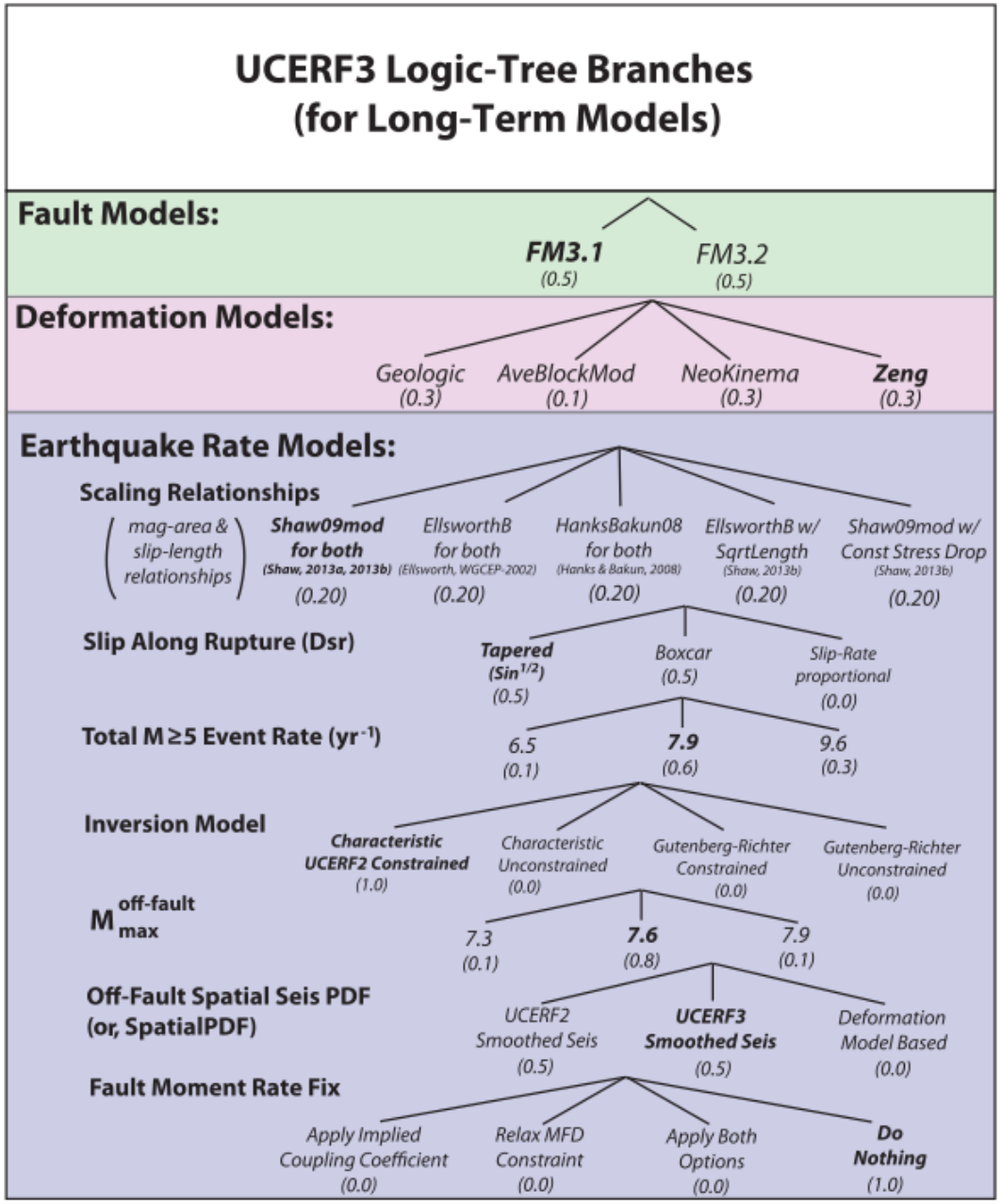
  Many assumptions

  Difficult to test due to long recurrence times

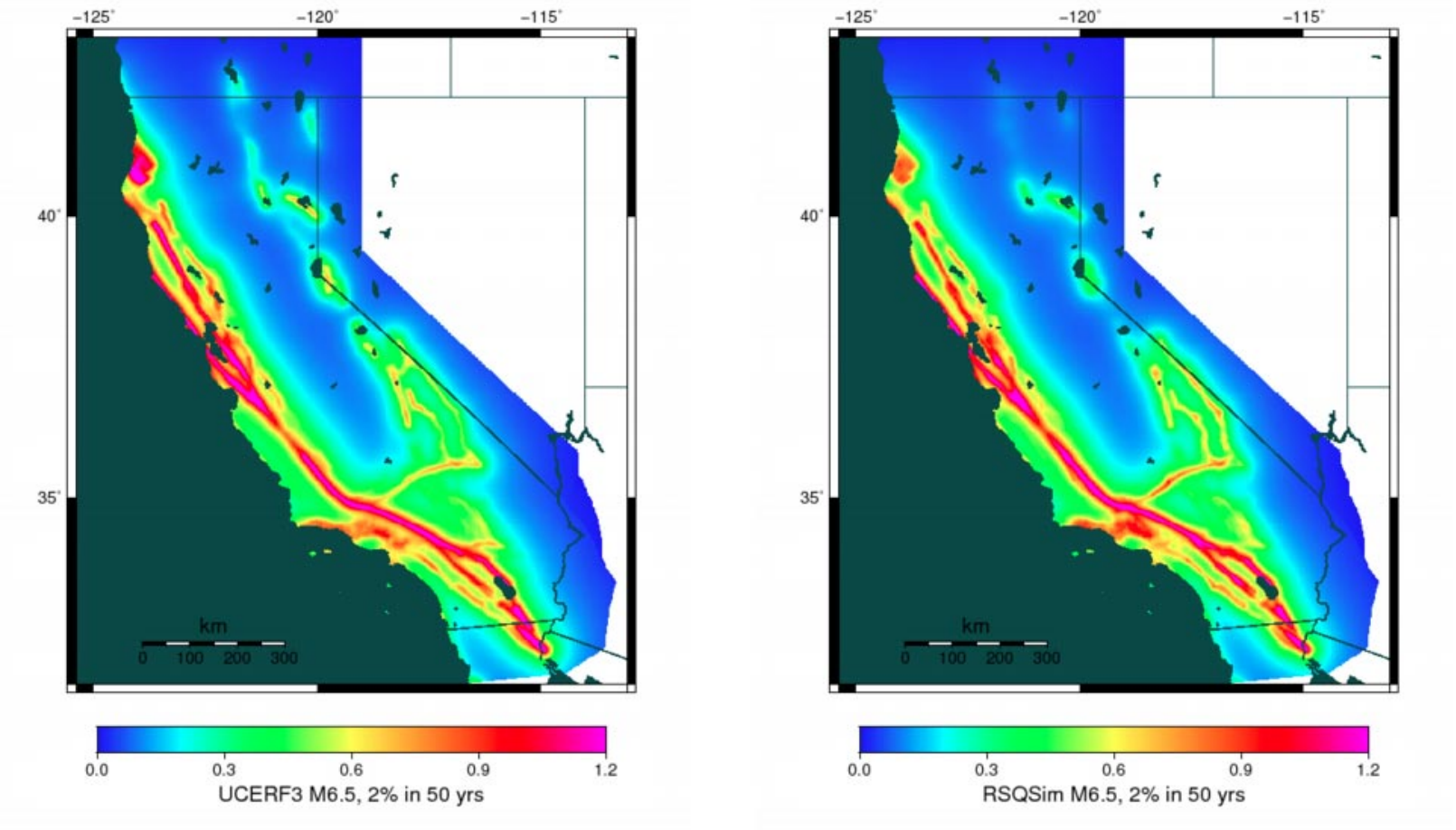
  Whole construct has been questioned

  Society investing huge resources on uncertain ground

Logic Tree for Uncertainties



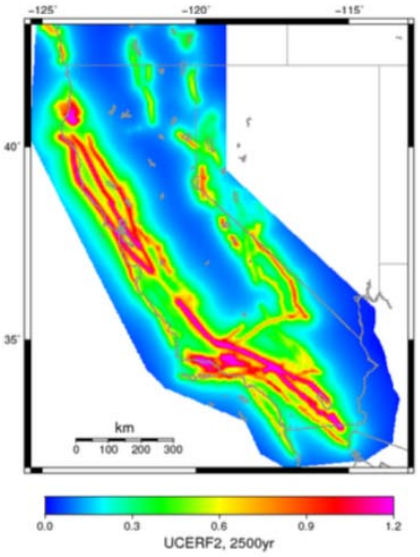
Standard Hazard Measure

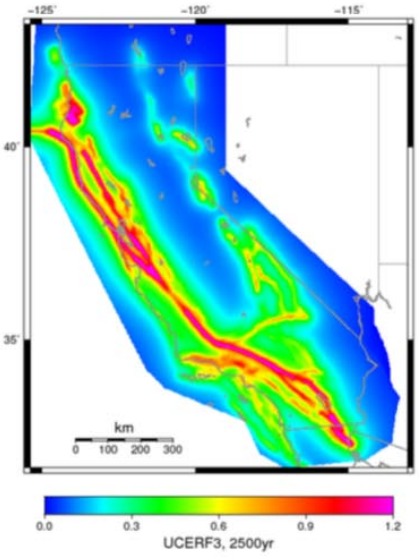


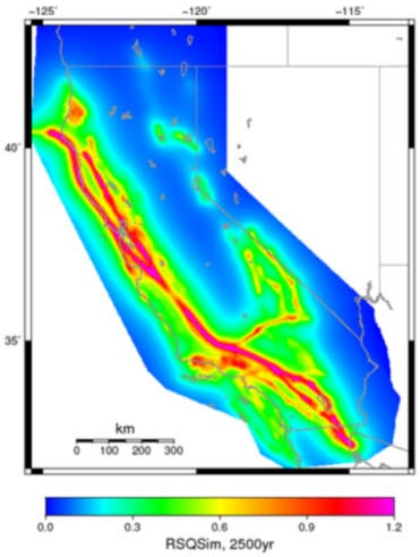
UCERF3 Model

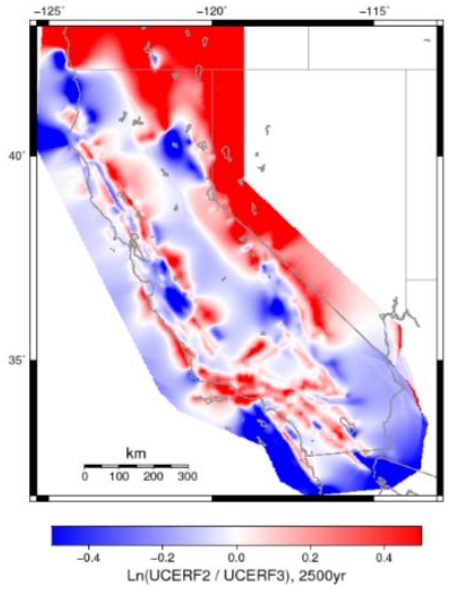
- On-fault hazard only
- Remarkable agreement!! Why?!
- Also push further into other measures

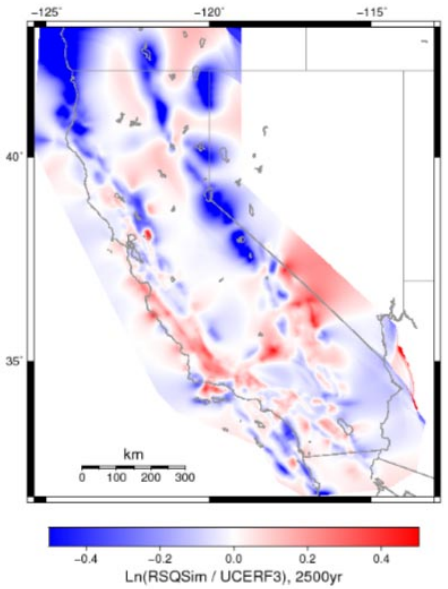
Model closer to UCERF3 than UCERF3 is to UCERF2







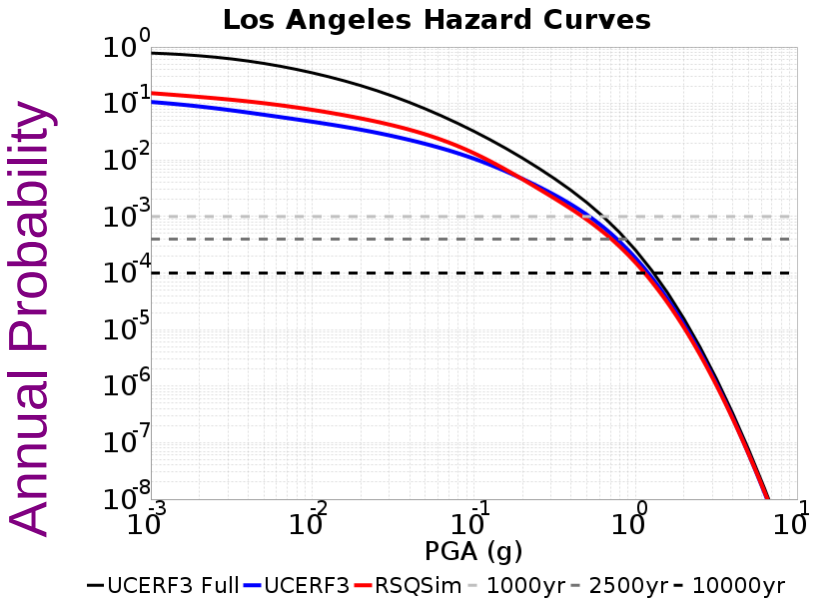




UCERF2/UCERF3

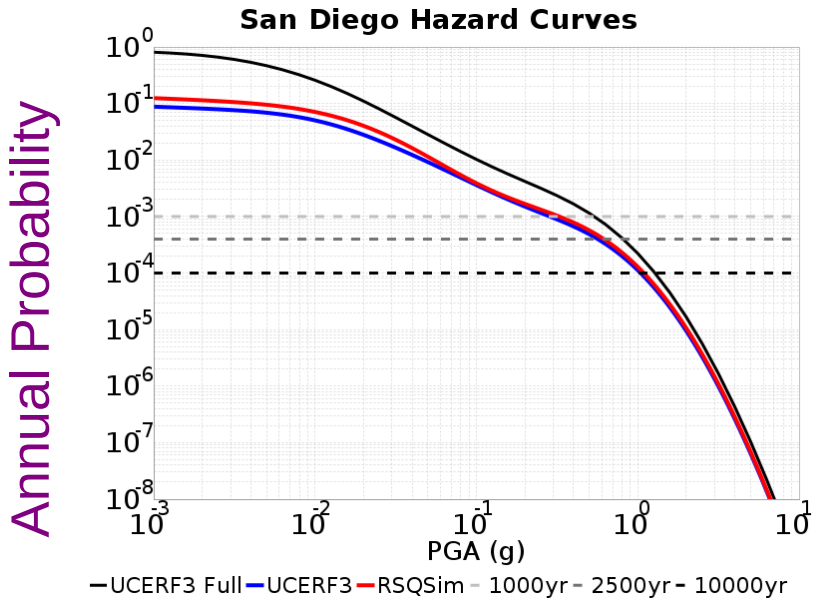
Model/UCERF3

Full hazard curves at a point



PGA (g)

Los Angeles

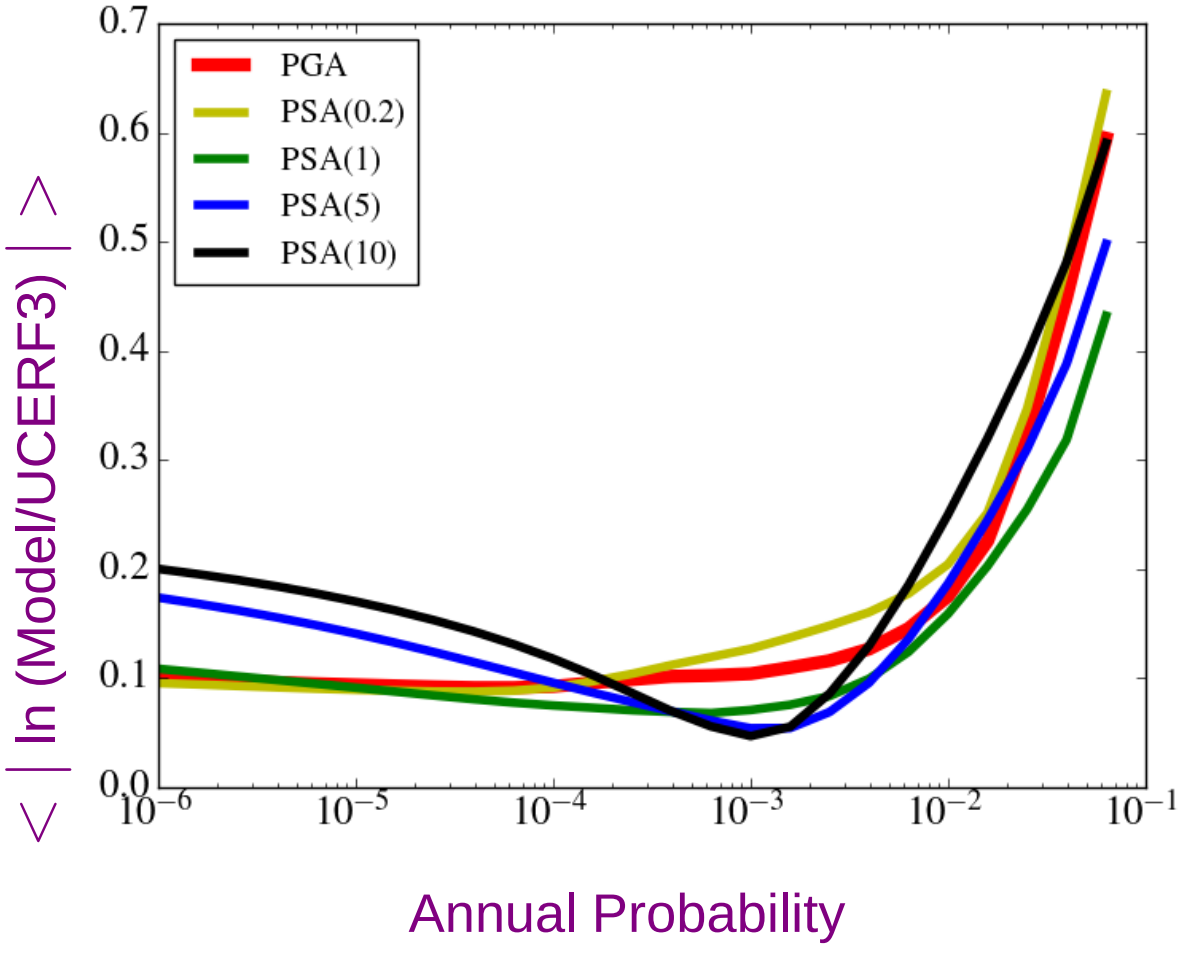


PGA (g)

San Diego

- Hazard curves agree well, especially at low prob.

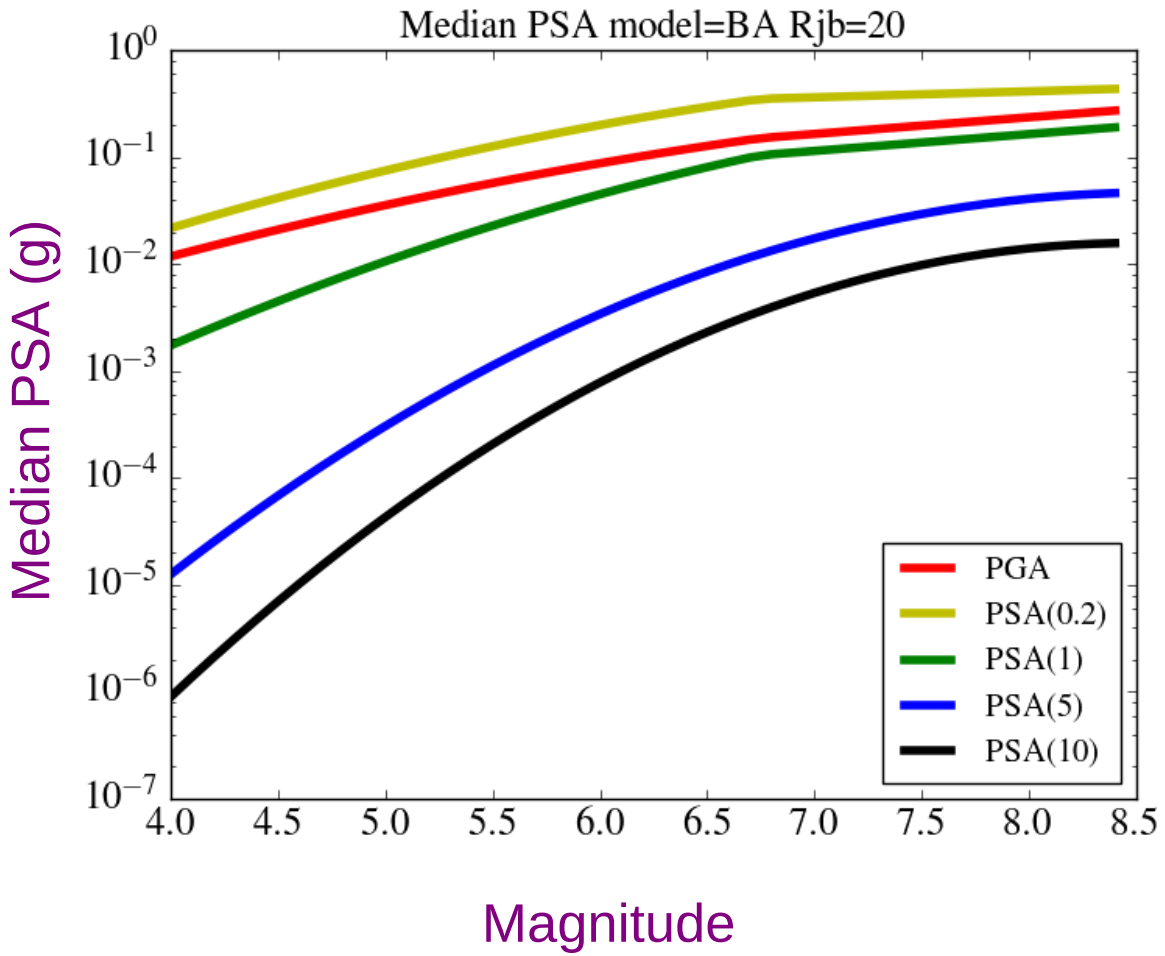
Other spectral periods



- Mean Absolute Ln Ratio small useful measure
- Agrees well annual prob $<$ repeat time large events
- Agree well over wide range of engineering interest (0.2-1s)

[Rule of thumb .1s/story in building]

Why Agree?: Weak Mag Dependence at High f



- Weak magnitude dependence at large magnitudes and high frequencies
- Also M7.5 vs 3 M7.2: higher mean vs more chances

Ready for Prime Time

- Ready for this application
- Useful voice for ensemble forecasts
- Ready to be shot down:
  what are behaviors missing relative to observations?
  (NOT what physics is missing)

Push Harder

- Map out areas of agreement and divergence
- Explore epistemic uncertainties further
- Time dependent hazard
- Robustness to scale of modeling– larger and smaller
- Robustness raises question of even simpler models, and how different answer can be given faults and GMM
- Push to test ground motions from model ruptures

  Ground motion models playing big role.

  Can we do better?

  Probe of source physics

  Testing ground motions directly promising!

Hazard Conclusions

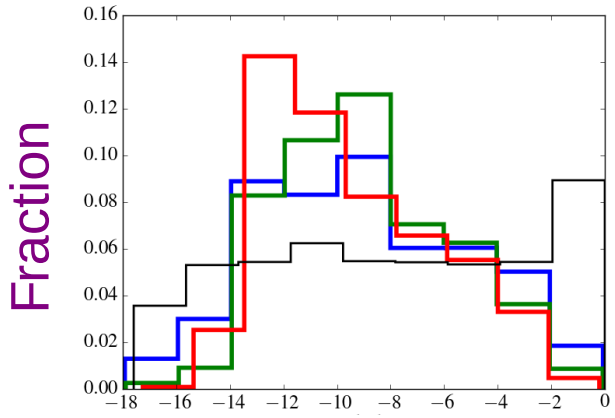
- Remarkable agreement: Mean Absolute Ln small
  useful measure for complex system comparison
- Remarkable agreement over range of engineering
  importance
- Insensitivities of some hazard measures
  to known unknowns
- Simulators ready to contribute
- Simulators new tool for exploring epistemic uncertainties
- Simulators require fewer parameters and assuptions
- Profound cross-validation of PSHA triangulation replication
- Hazard measures very forgiving

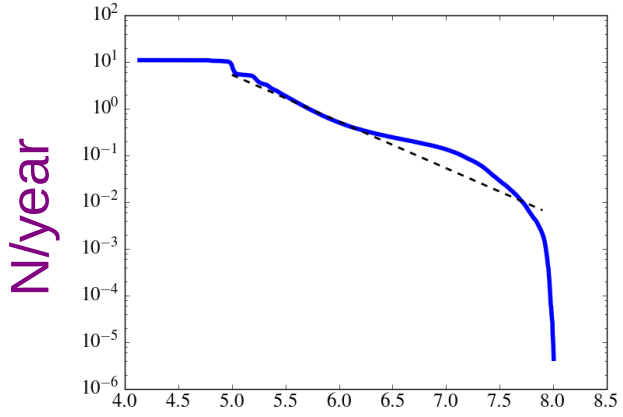
See [Shaw, et al., *Science Advances*, 2018]

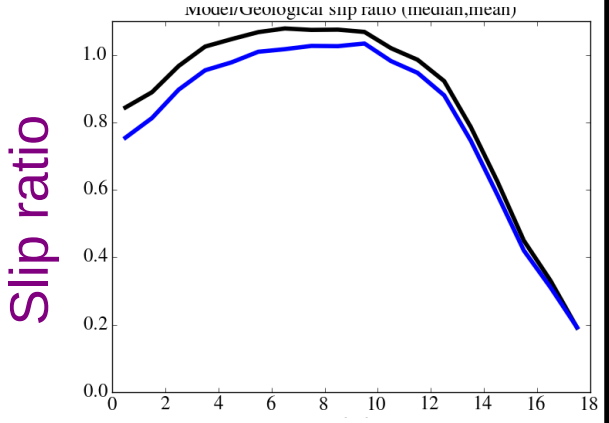
Simulators: How to and how not to use

- Robustness and Sensitivity
- Differences:
  - Creeping section (physical modeling)
  - San Gorgonio pass (fault connectivity and geometry)
  - Distribution of sizes
- Beyond backslip: hybrid loading
- How not to use: If overly sensitive
- Simulators doing so well need to find ways it fails

Hybrid Loading







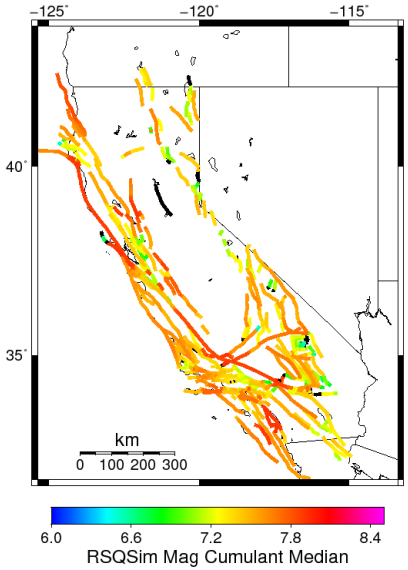
Hypocenter depths

Magnitude dist.

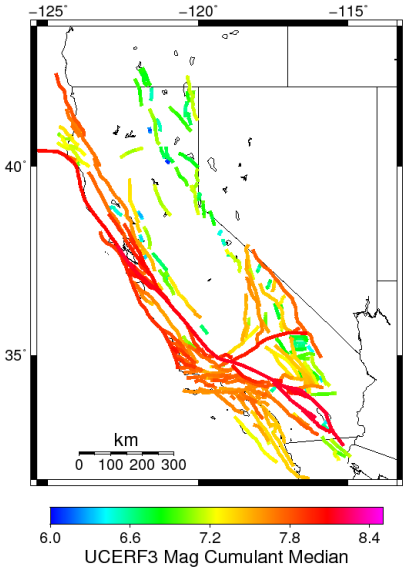
Slip(depth)

- Improvements in behaviors with hybrid loading
- Are physical implications underlying loading right?

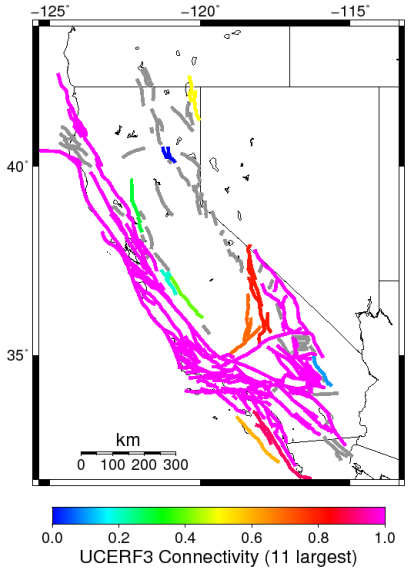
Dominant Magnitude differences and implications



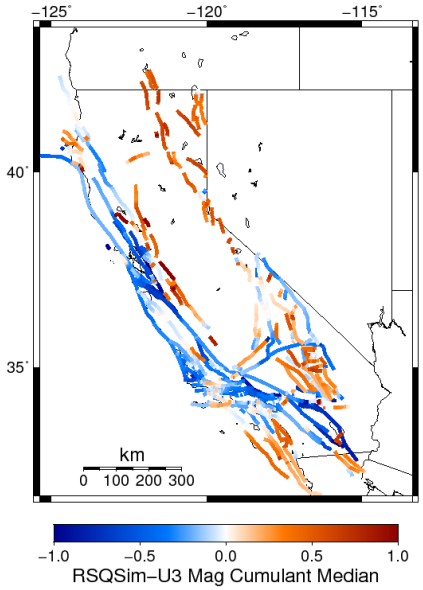
M* Model



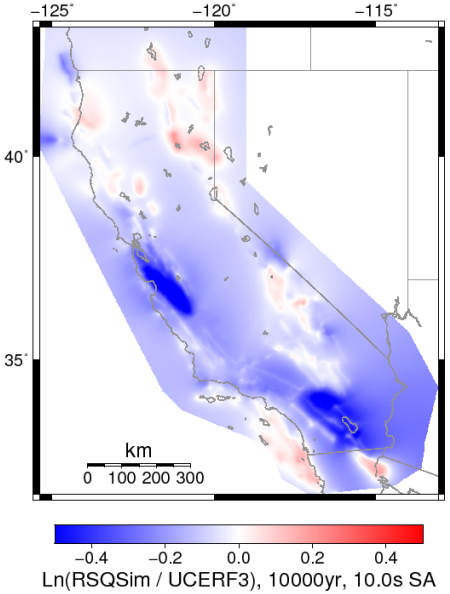
M* UCERF3



Connectivity UCERF3



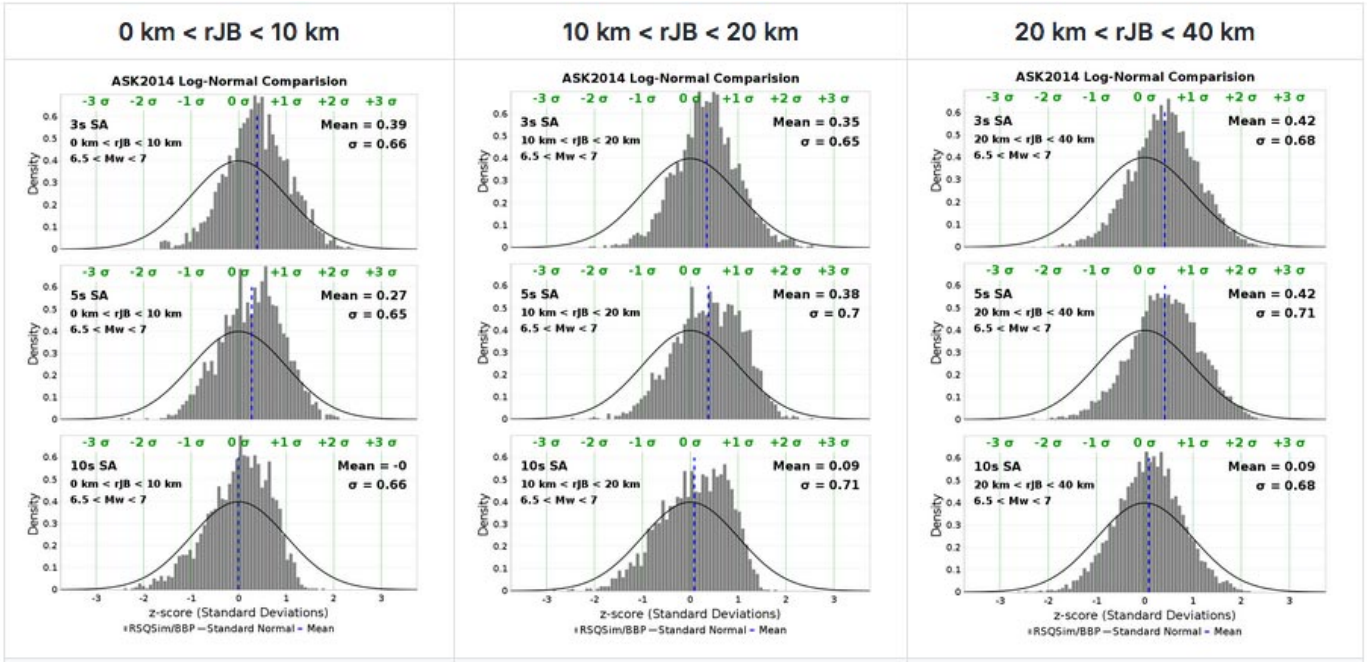
M* Model - UCERF3



ln Model/UCERF3 PSA(10)

Trying to match ground motions

← Spectral Period



Distance from rupture →

Magnitudes M6.5-7 PSA(T) relative to GMM

- Aiming to match distributions of ground motions
- In the ballpark
- See Kevin Milner, et al. poster #032 for lots more

Ned's List

Or, can they answer any of the following questions (relevant to current forecasting methods):

- The plausibility of various multi-fault rupture possibilities?
- Which magnitude-area and/or slip-length scaling laws are viable?
- Average slip along rupture (over multiple occurrences) especially for multi-fault events?
- Magnitude frequency distribution near faults (non Gutenberg-Richter)?
- How creep influences rupture distributions (e.g., what do large SAF creeping-section events look like)?
- Influence of elastic rebound (can a large triggered event rupture from well within the rupture zone of the main shock)
- Spatiotemporal clustering (e.g., is ETAS really a good, or the best proxy for M≥6.5 events?)
- Paleo hiatus question identified by David Jackson (models predict that we should have seen more events)?
- The influence of other time dependencies (e.g., swarms, super cycles, mode switching)?