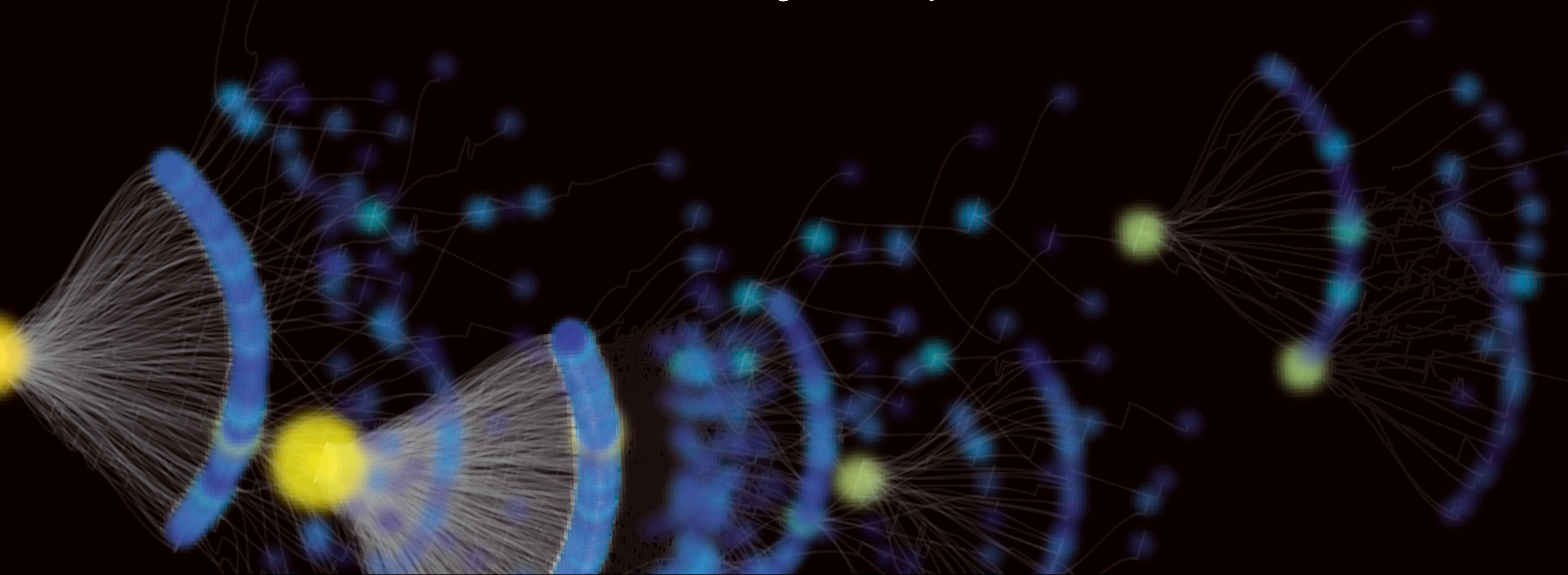
Foreshocks are not predictive of future earthquake size

Morgan Page, Karen Felzer, and Andrew Michael
U.S. Geological Survey



Foreshocks are not predictive of future earthquake size

(but nevertheless contain quite a bit of predictive power)

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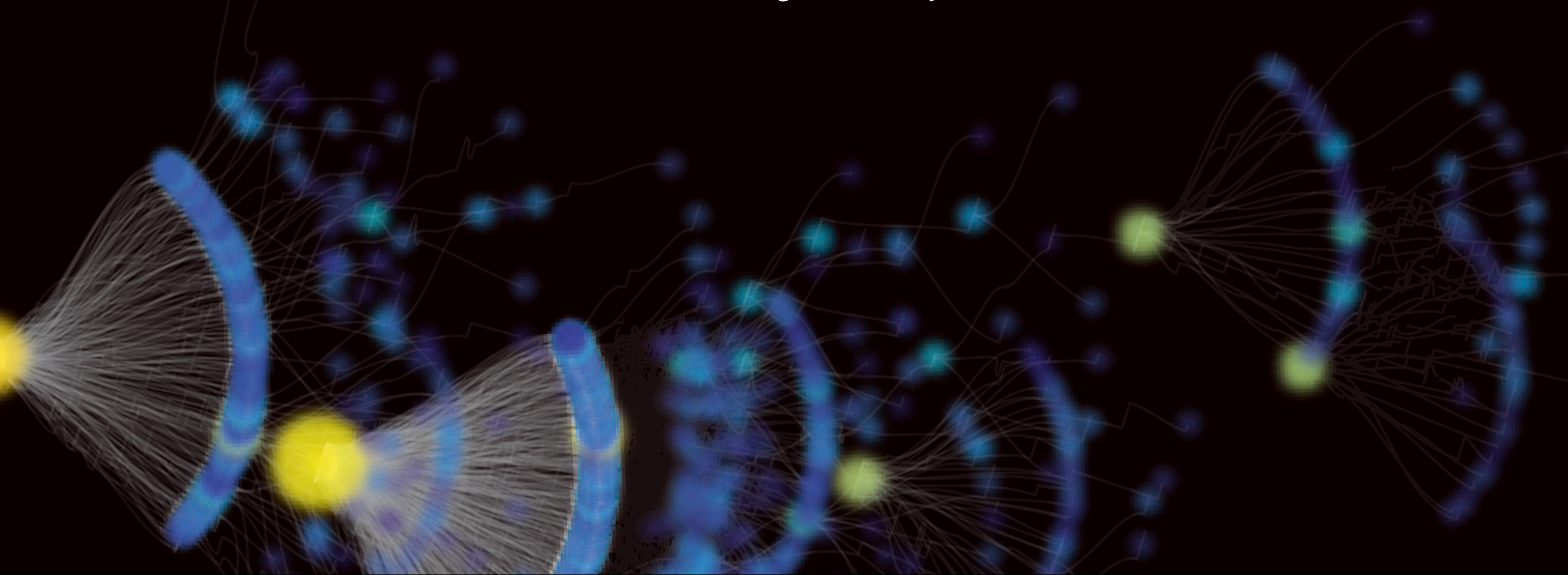
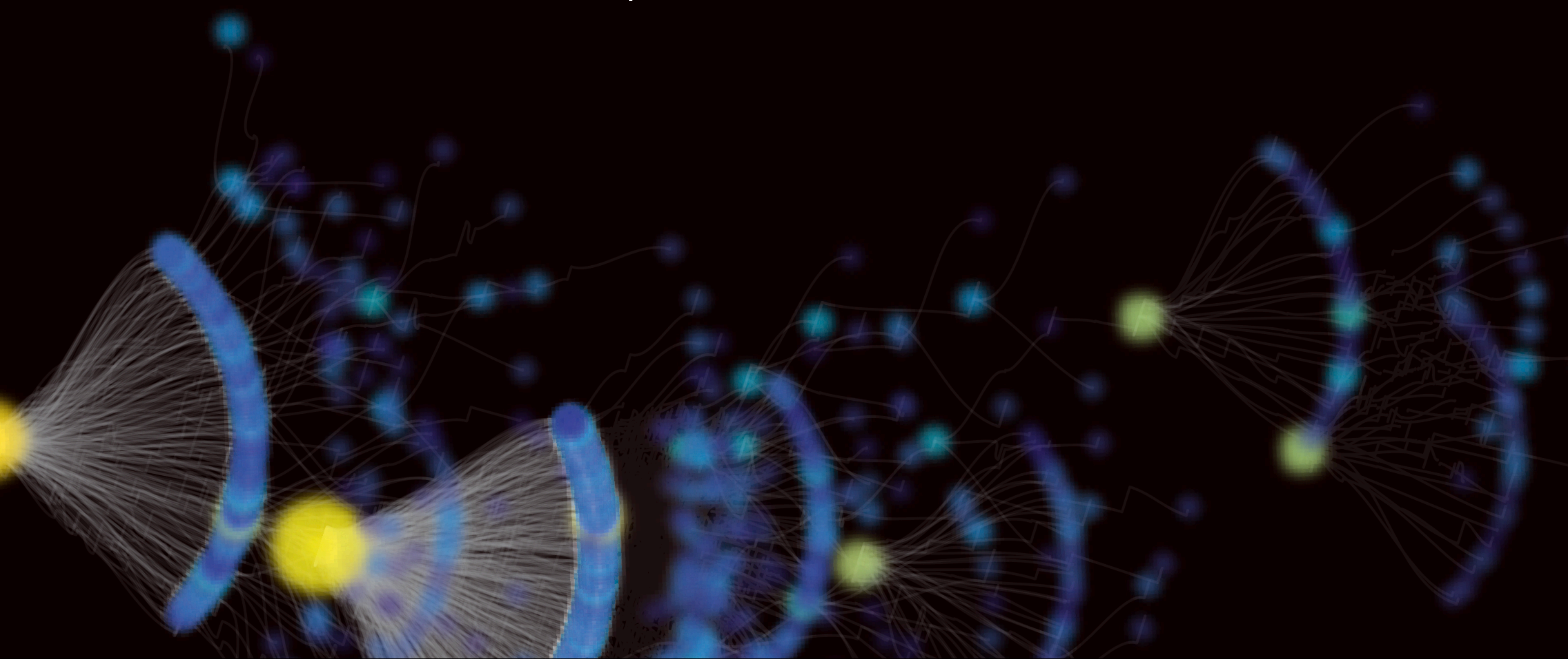


The Cascade Model

Small and large earthquakes nucleate in the same way

There is some probability that a given earthquake will grow large, but size is unpredictable ahead of time



The Cascade Model

Small and large earthquakes nucleate in the same way

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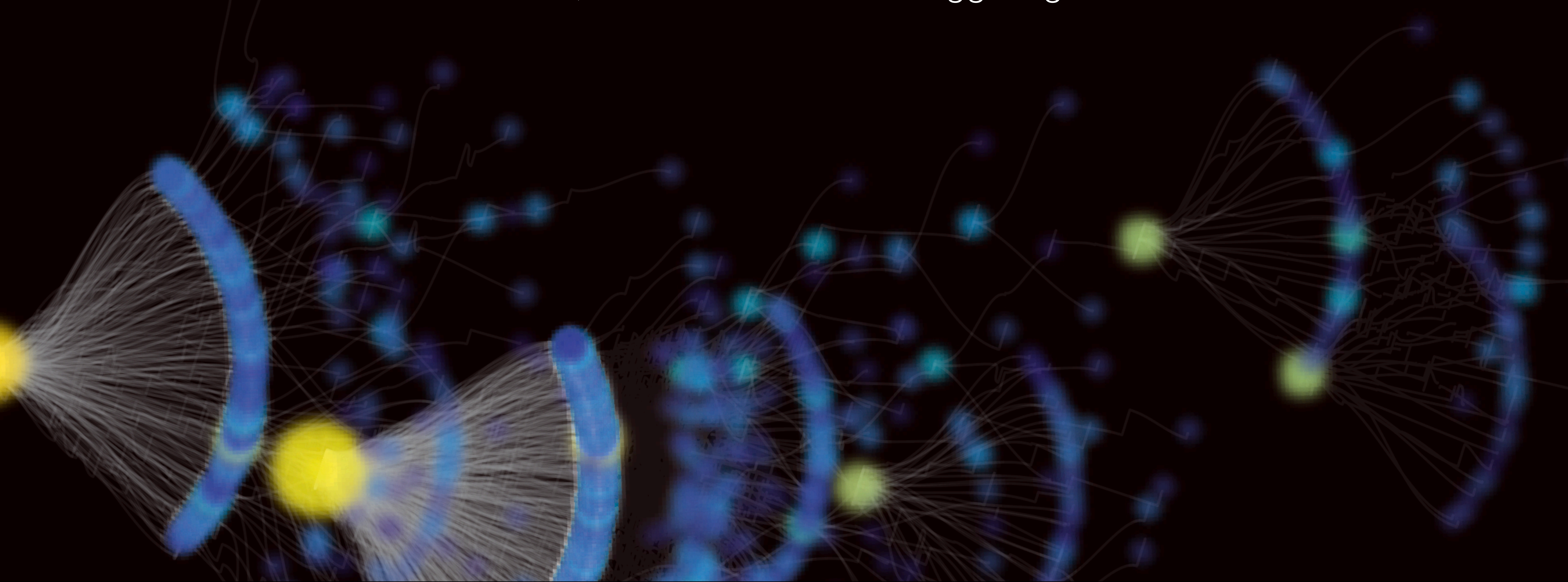
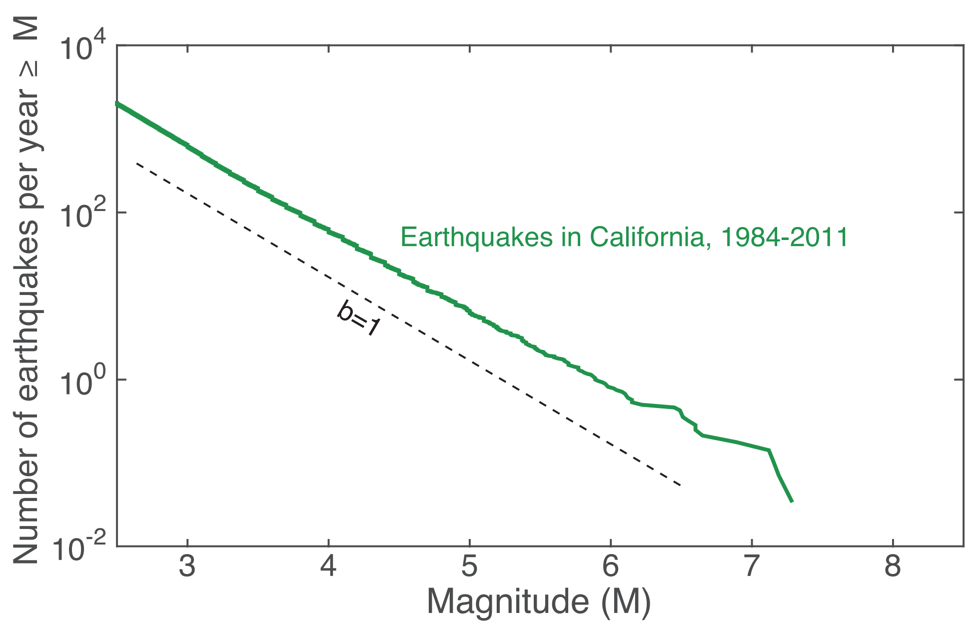
Distribution of stress heterogeneities determines size of mainshock, not characteristics of triggering event



The Basics of Earthquake Forecasting

The Statistical Seismologist's Approach



Gutenberg-Richter Magnitude Scaling

$$N(M) \propto 10^{(a-bM)}$$

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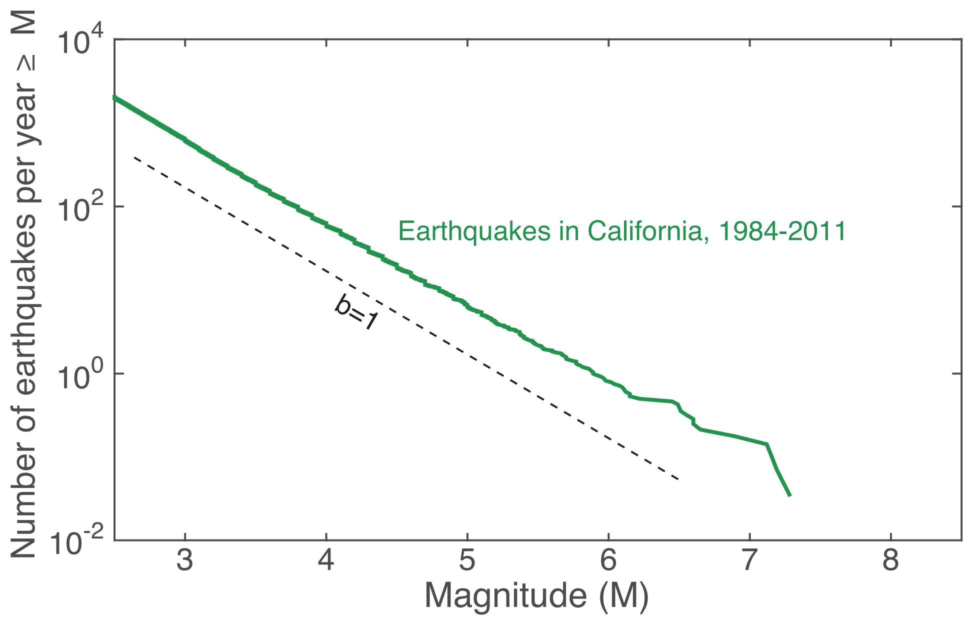

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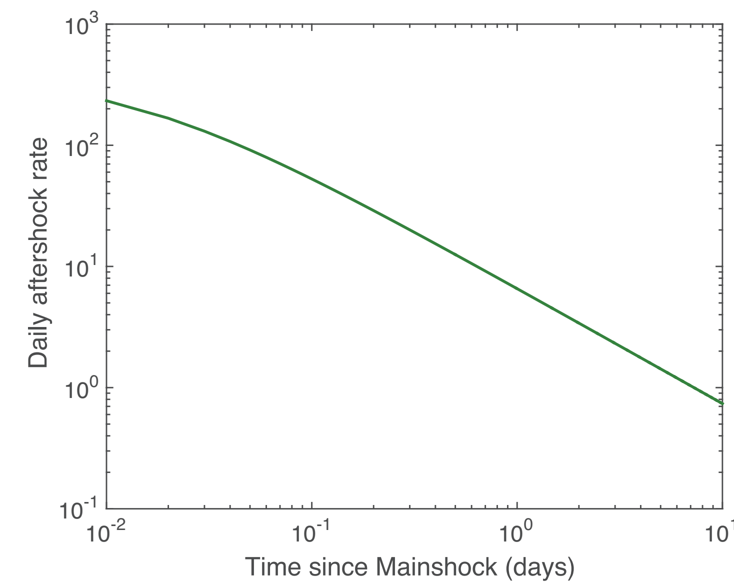
Omori Decay of Aftershock Rate

$\lambda(t) = (t+c)^{-p}$



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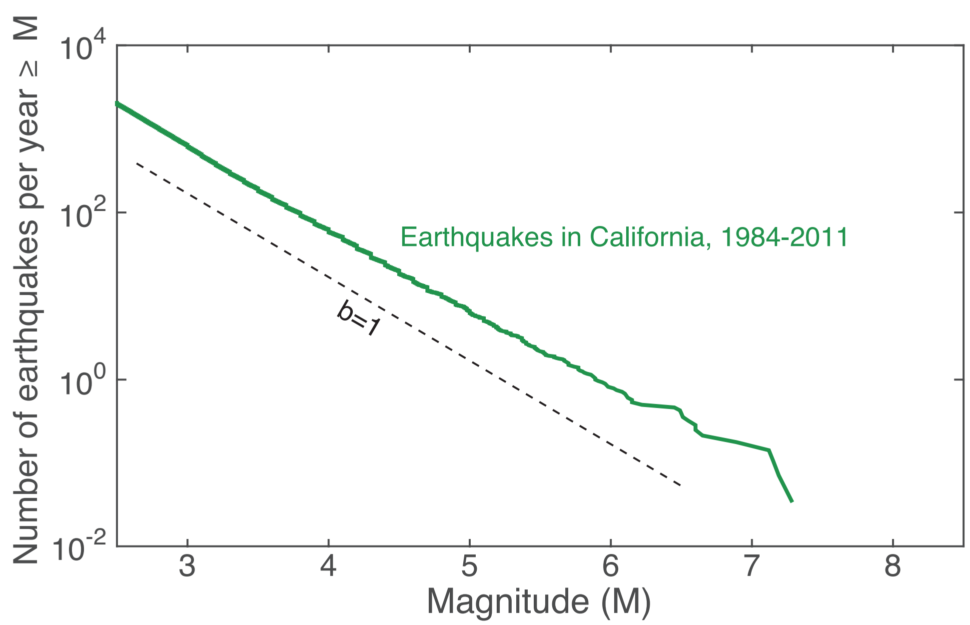

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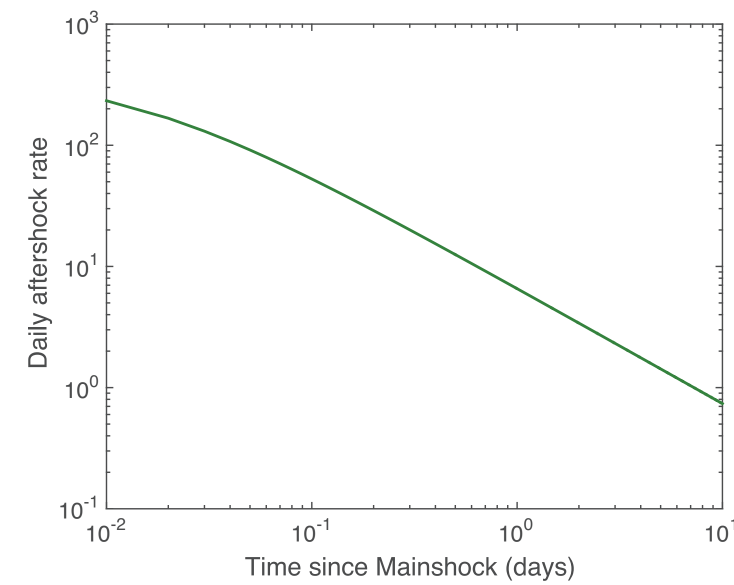

Big earthquakes trigger more aftershocks

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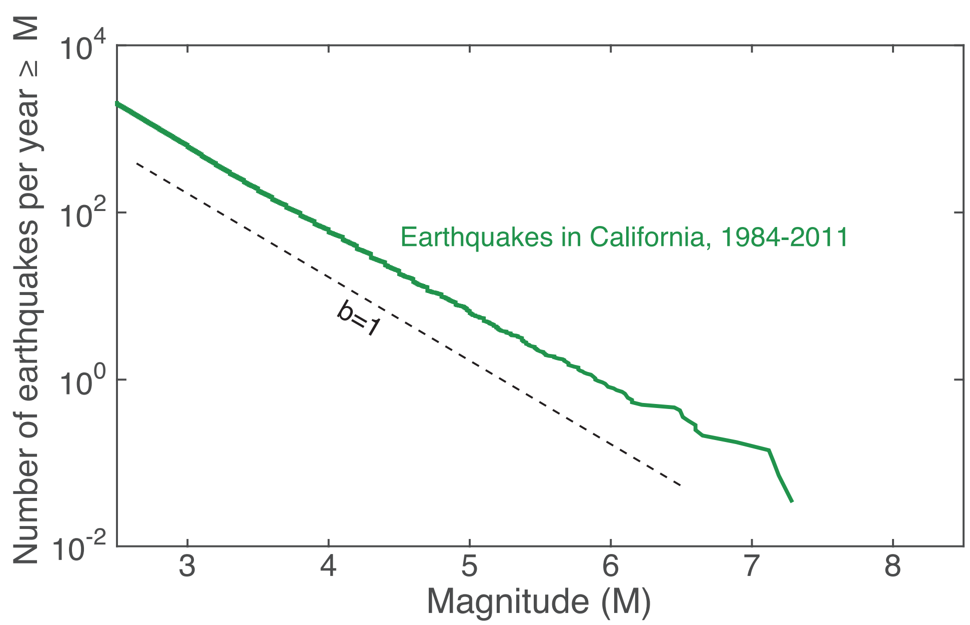
The Statistical Seismologist's Approach



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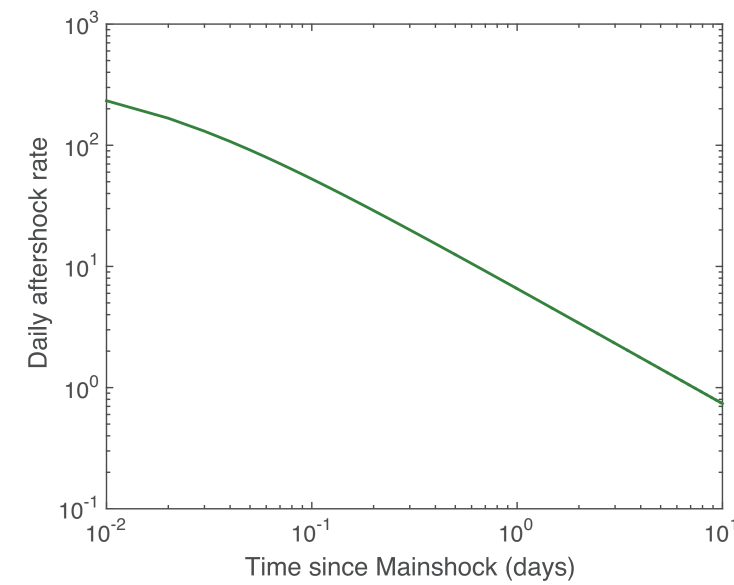

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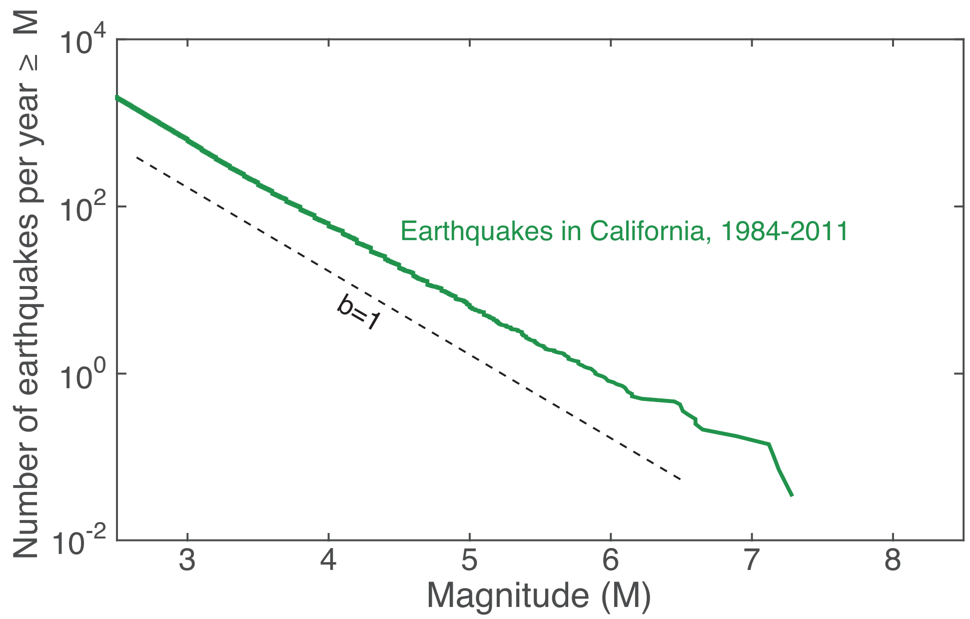
Aftershock rates decay with distance from the mainshock

$$p(r) \propto N(r)\left(r^2 + d^2\right)^{-\gamma/2}$$

The Basics of Earthquake Forecasting

The Statistical Seismologist's Approach



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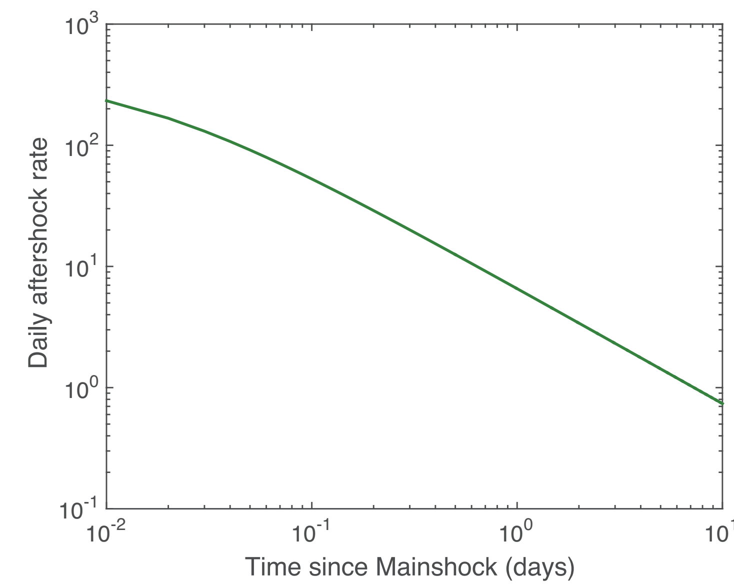

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These scaling laws are used in short-term forecasting models like ETAS (Ogata, 1988) and STEP (Gerstenberger et al., 2005)

Alternatives to cascade model

Pre-slip

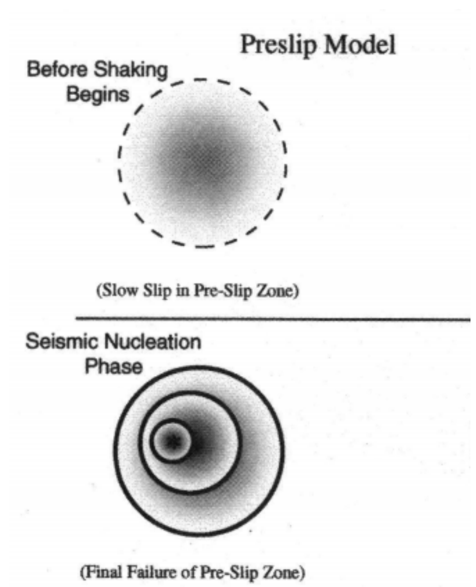
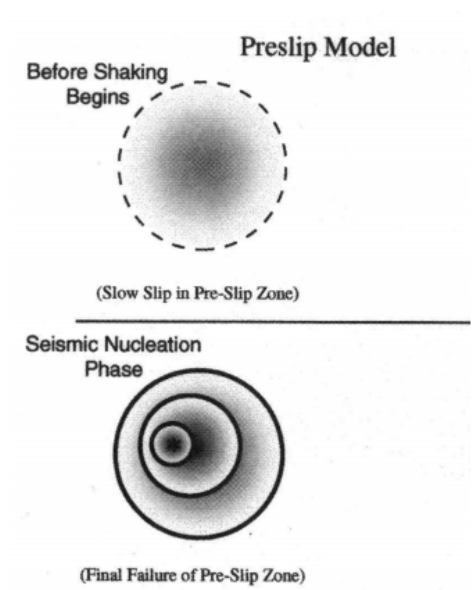


figure from Vidale et al. (2001)

Foreshocks result from aseismic slip in the nucleation zone of future large earthquake

Alternatives to cascade model

Pre-slip



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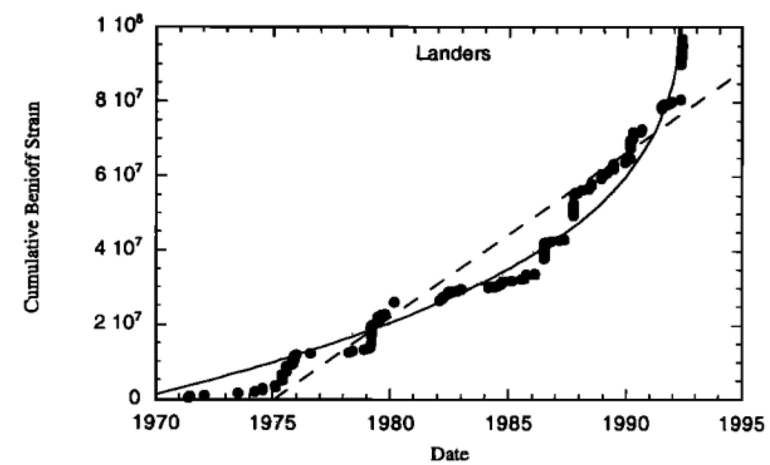
Foreshocks result from aseismic slip in the nucleation zone of future large earthquake

Accelerating Moment Release (AMR)



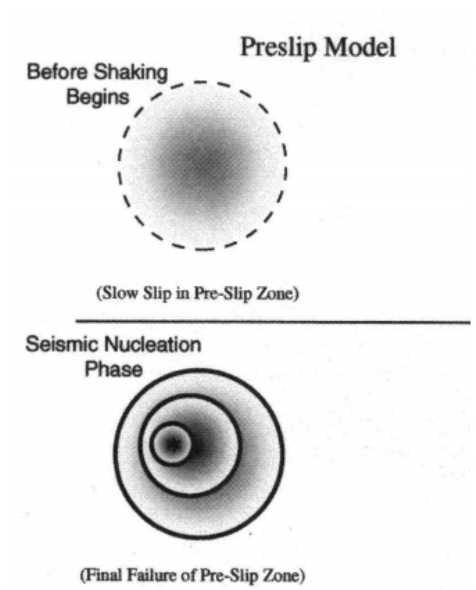
Bowman et al. (1998)

Hardebeck et al. (2008) showed the hypothesis was statistically insignificant

(ETAS catalogs can produce just as much apparent acceleration)

Alternatives to cascade model

Pre-slip



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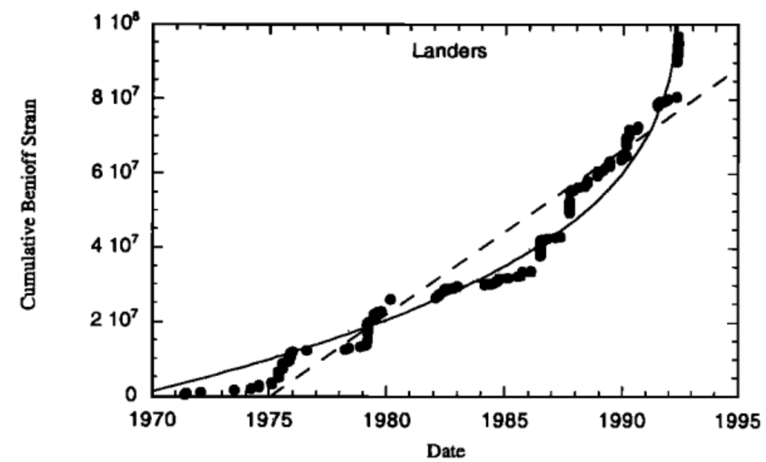


Bowman et al. (1998)

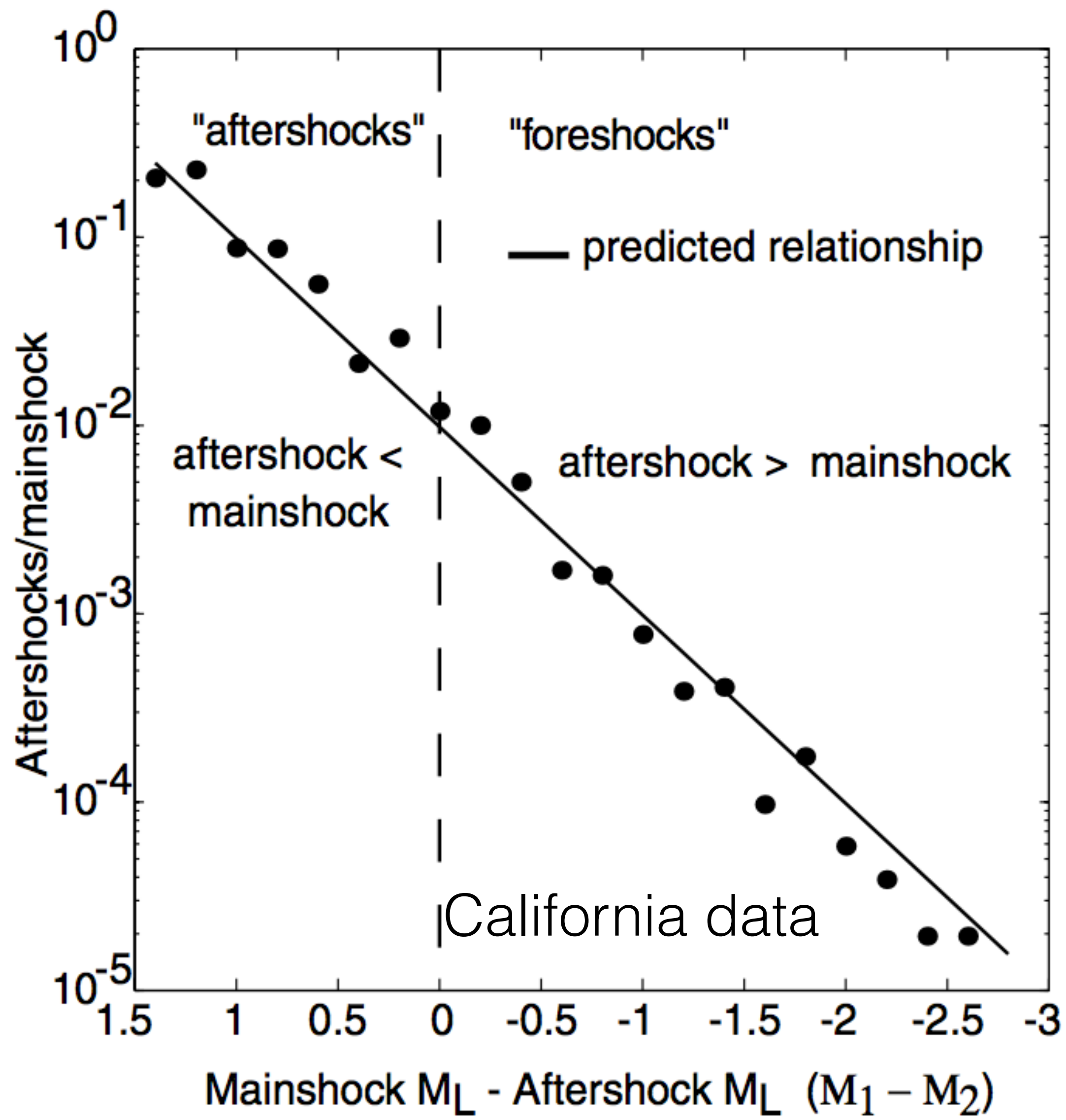
Foreshocks result from aseismic slip in the nucleation zone of future large earthquake

Hardebeck et al. (2008) showed the hypothesis was statistically insignificant

Unlike cascade model, these models hypothesize that foreshocks are “different” from other earthquakes and are predictive of future earthquake size

Cascade Model Predictions

The foreshock rate and the aftershock rate follow the same trend ✓

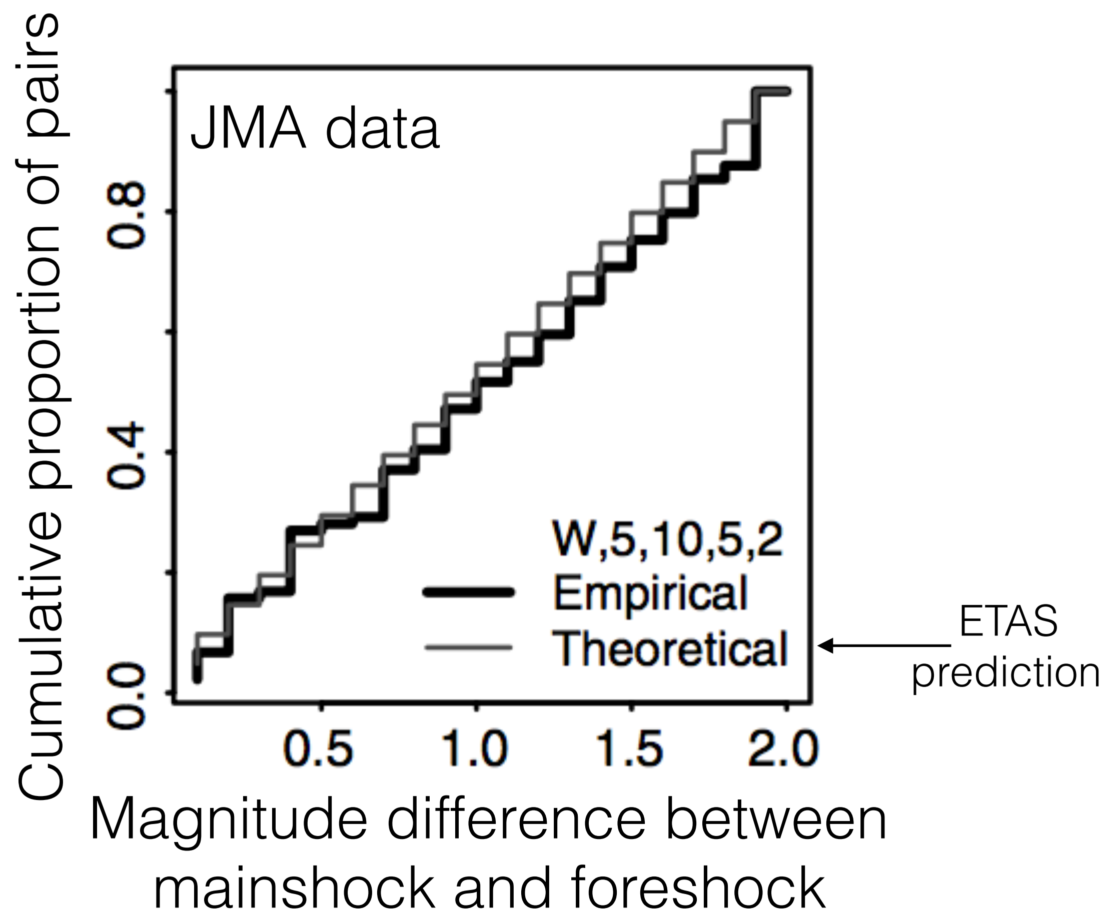


Given the aftershock rate, you can predict the foreshock rate, suggesting they represent the same process

Felzer et al. (2004)

Cascade Model Predictions

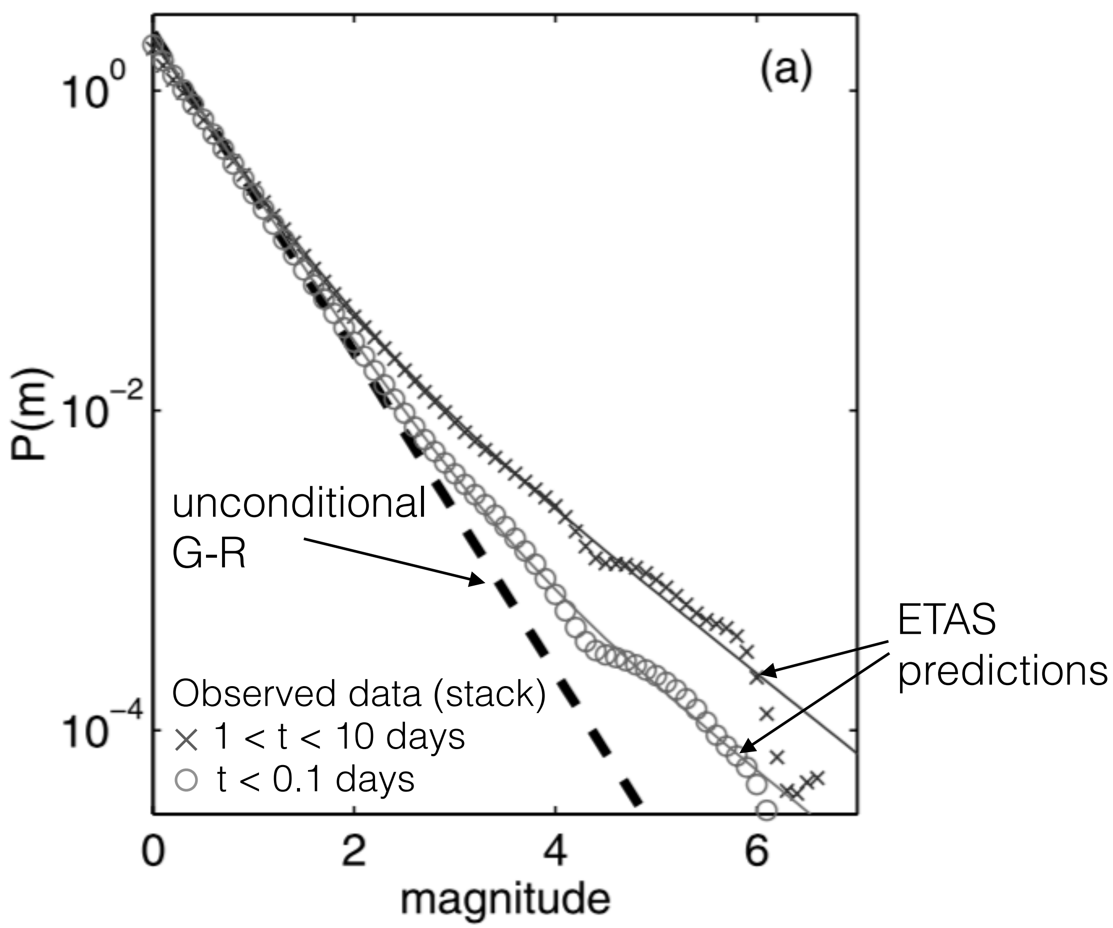
The magnitude distribution of foreshocks is uniform ✓



Smythe et al. (2011)

Cascade Model Predictions

Apparent decrease in b-value prior to mainshocks ✓

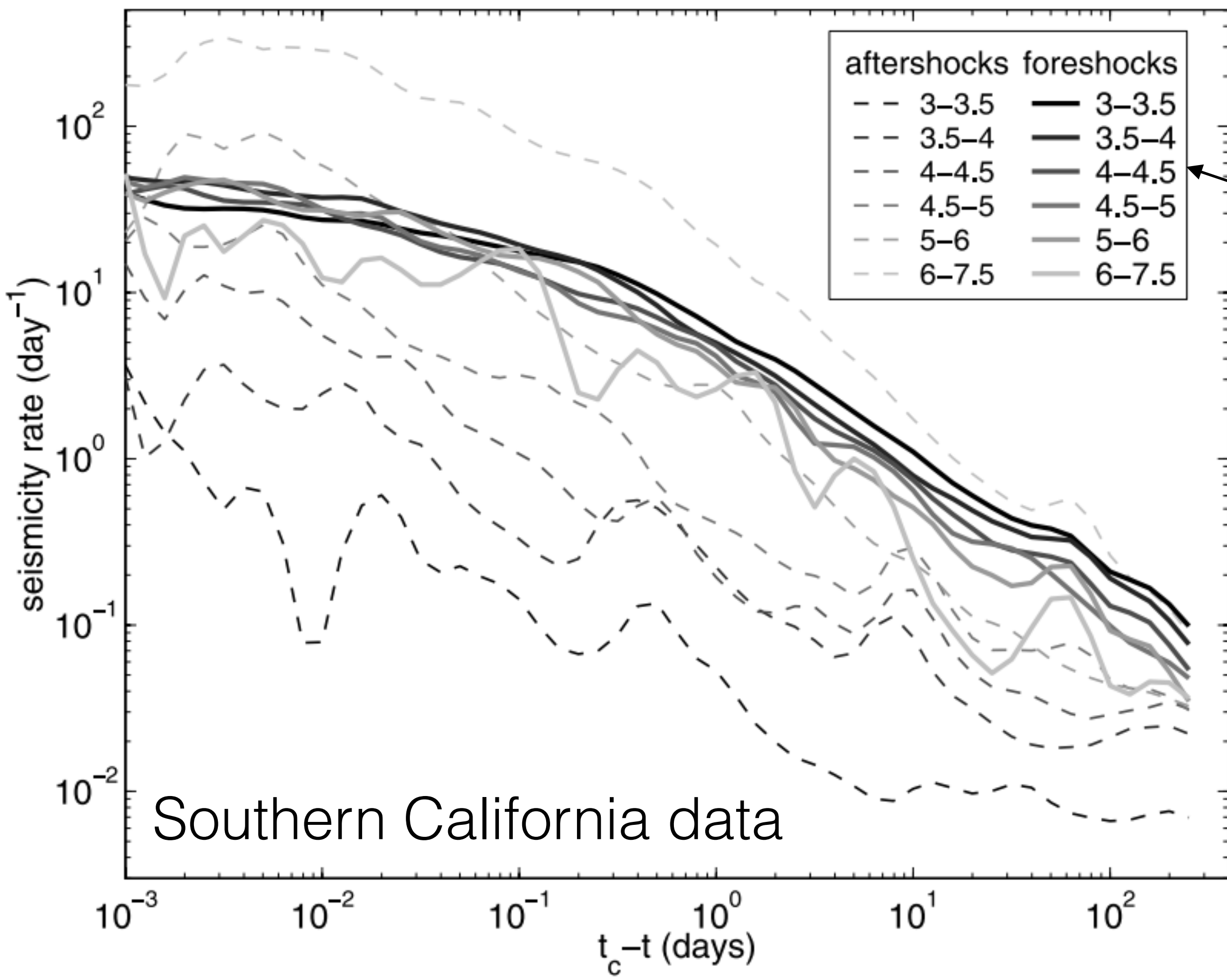


Helmstetter et al. (2003)

Larger earthquakes are more likely to trigger an earthquake than smaller earthquakes (because they trigger more earthquakes), so the *conditional* magnitude distribution prior to stacked “mainshocks” has a lower b-value at higher magnitudes

Cascade Model Predictions

No significant correlation between number of foreshocks and mainshock size ✓



size of mainshocks

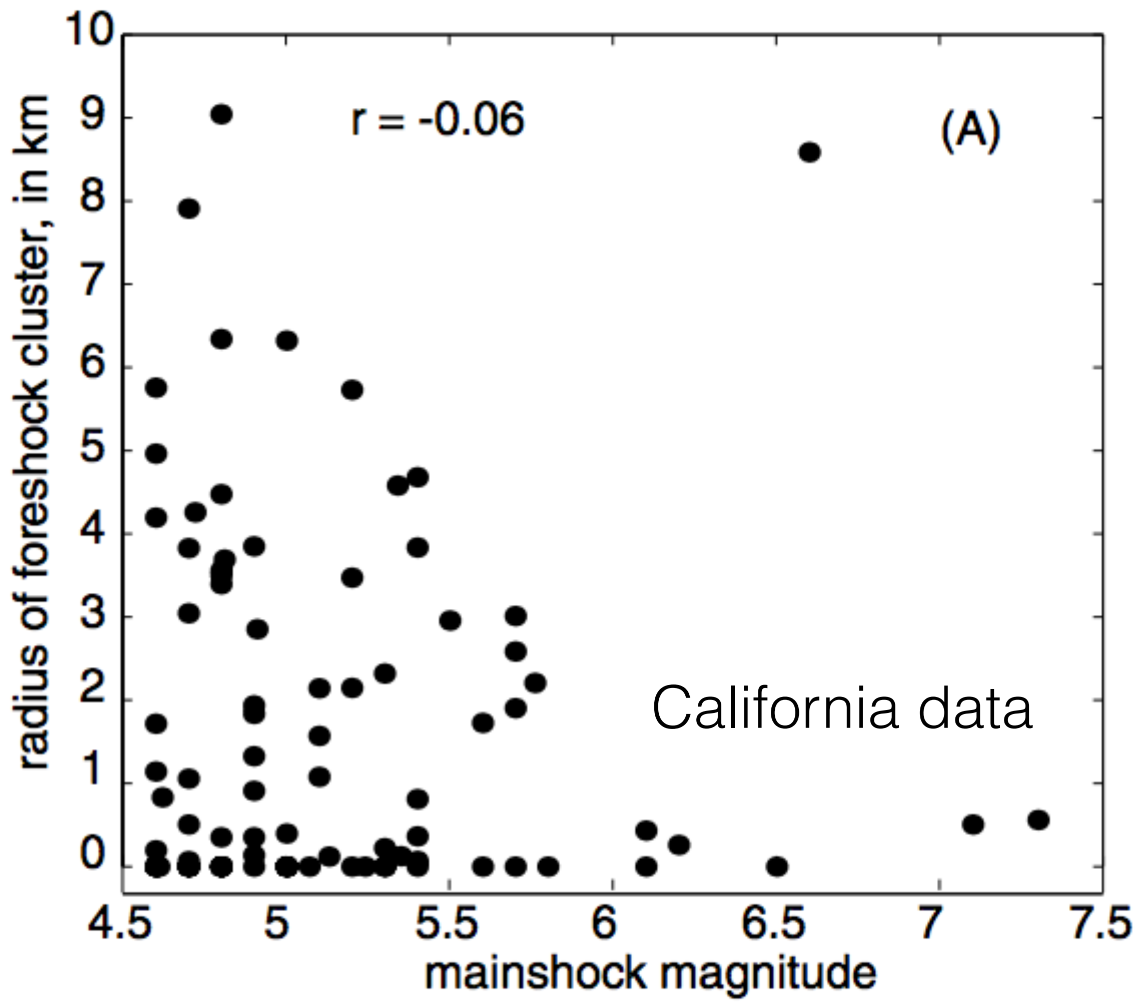
dashed lines - aftershock rates for different mainshock sizes

solid lines - foreshock rates for different mainshock sizes

Helmstetter and Sornette (2003)

Cascade Model Predictions

No significant correlation between foreshock area and mainshock size ✓



Felzer et al. (2004)

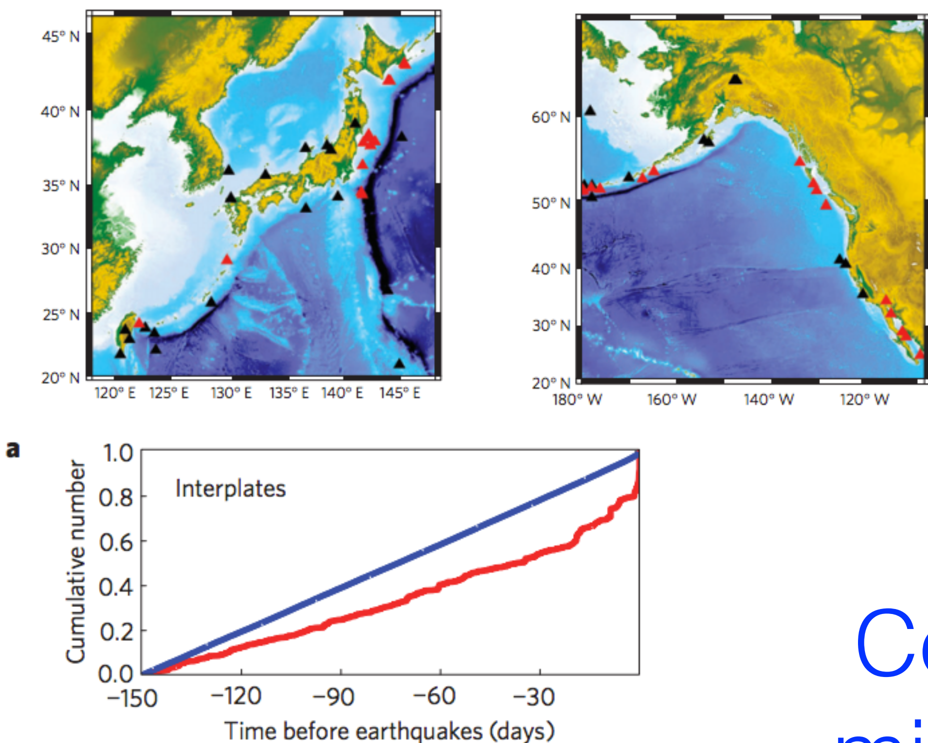
Recent Challenges to the Cascade Model

Bouchon et al. (2013)

nature geoscience | LETTERS
PUBLISHED ONLINE: 24 MARCH 2013 | DOI: 10.1038/NGEO1770

The long precursory phase of most large interplate earthquakes

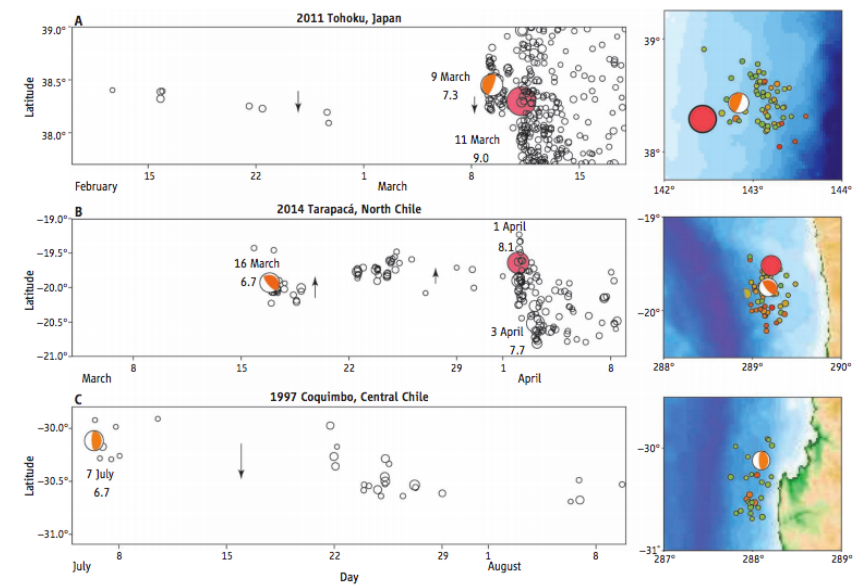
Michel Bouchon[1]*, Virginie Durand[1,2]*, David Marsan[2], Hayrullah Karabulut[3] and Jean Schmittbuhl[4]



Brodsky and Lay (2014)

Recognizing Foreshocks from the 1 April 2014 Chile Earthquake

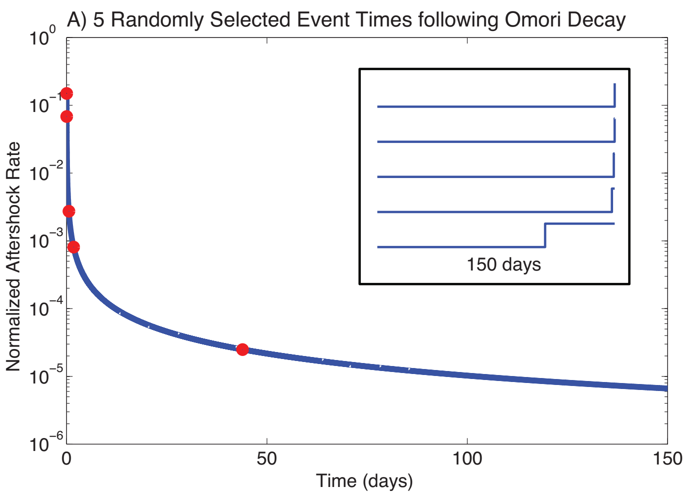
Emily E. Brodsky and Thorne Lay



Could slow slip or foreshock migration be used to forecast impending large earthquakes?

Inverse Omori Acceleration

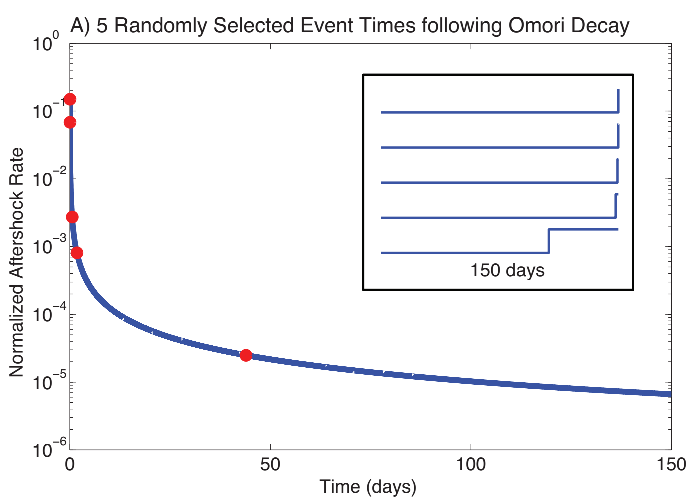
The Omori Law predicts “acceleration” in stacked foreshock sequences

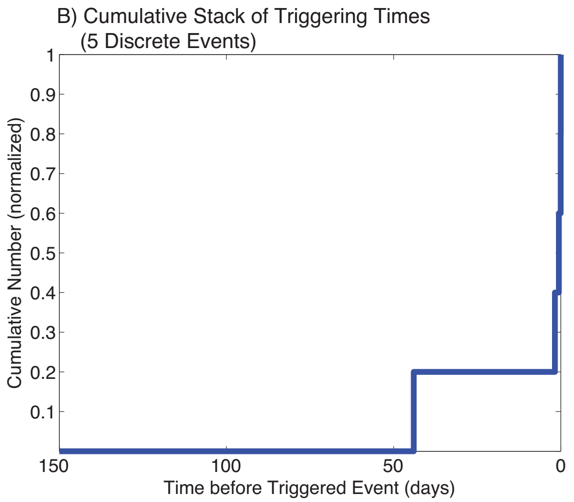


randomly selected times from Omori rate distribution

Inverse Omori Acceleration

The Omori Law predicts “acceleration” in stacked foreshock sequences





cumulative stack of these triggering times

Inverse Omori Acceleration

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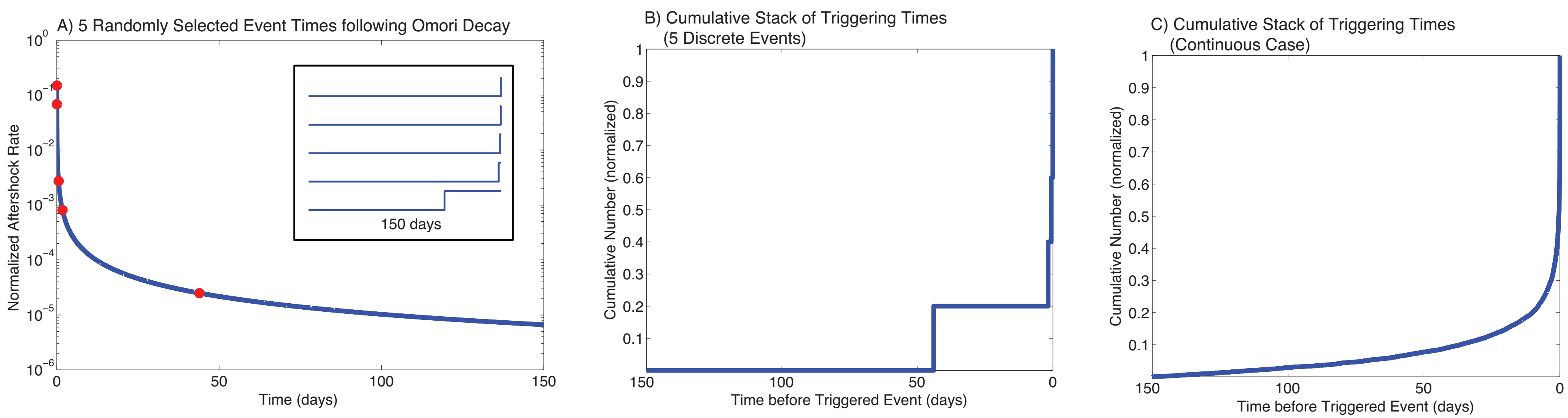

continuous version

Inverse Omori Acceleration

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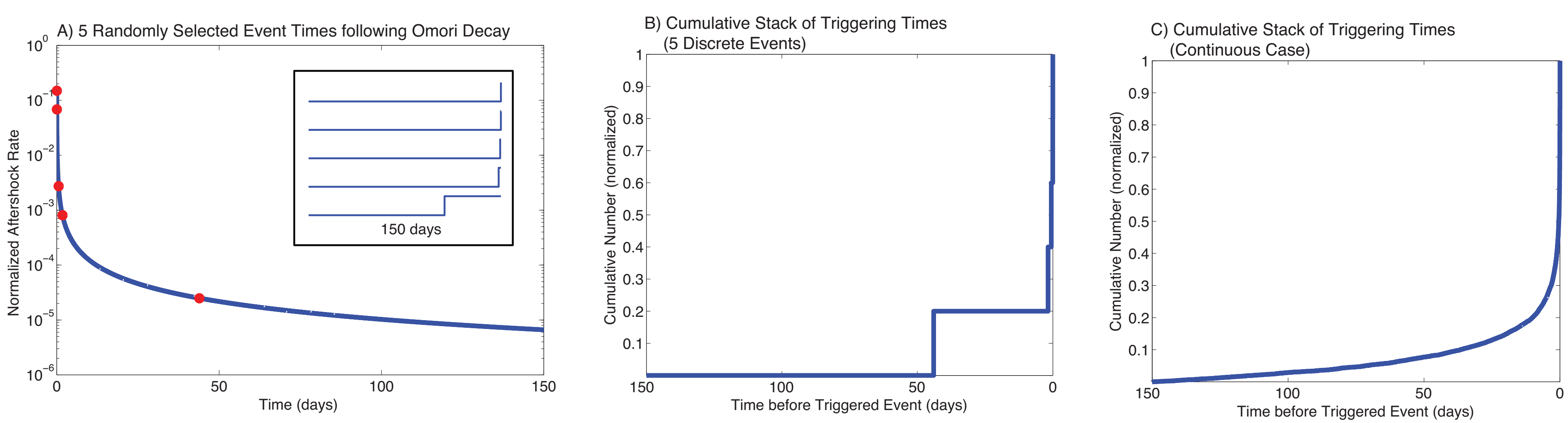
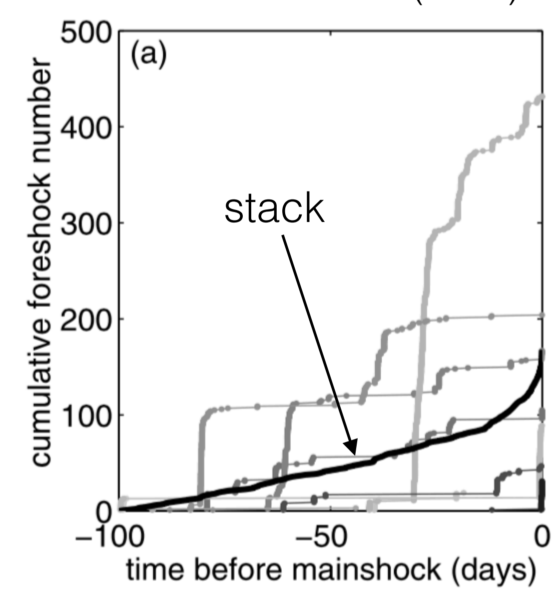


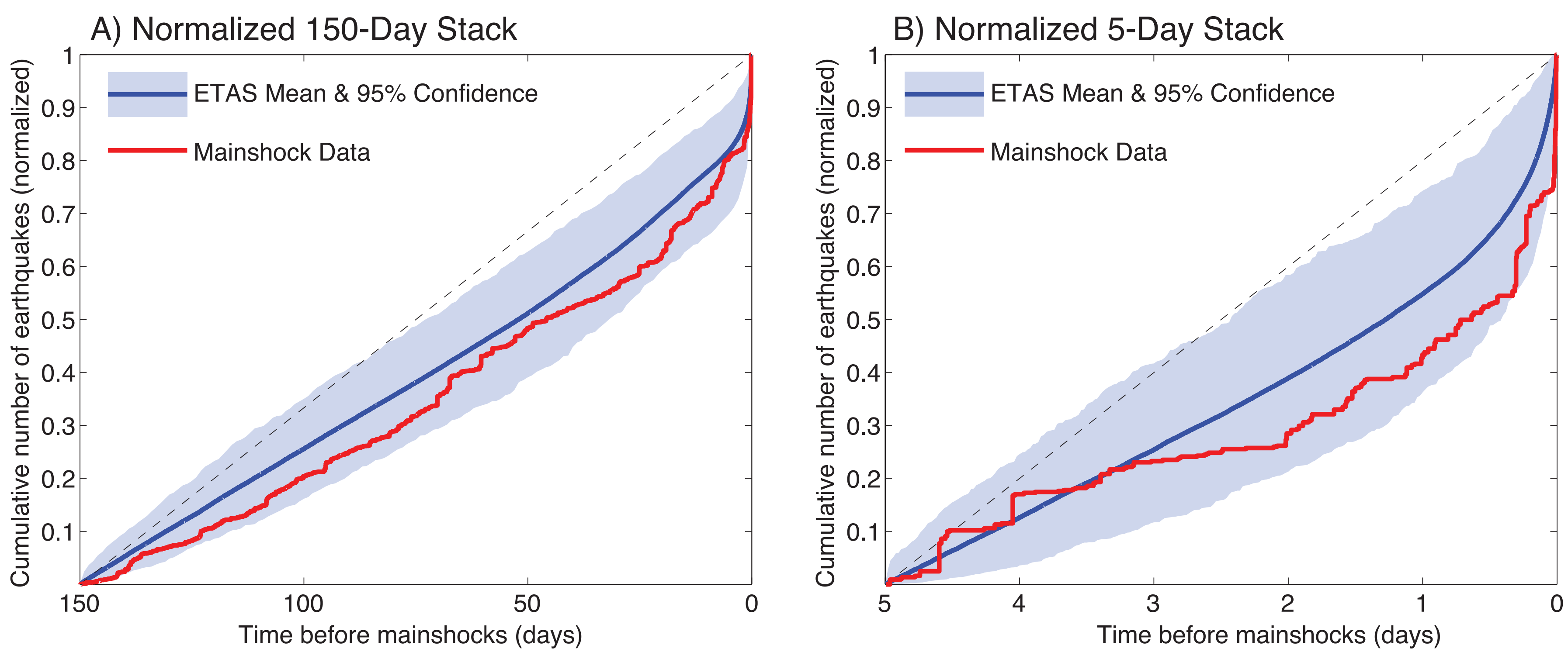
Helmstetter et al. (2003)



real data example

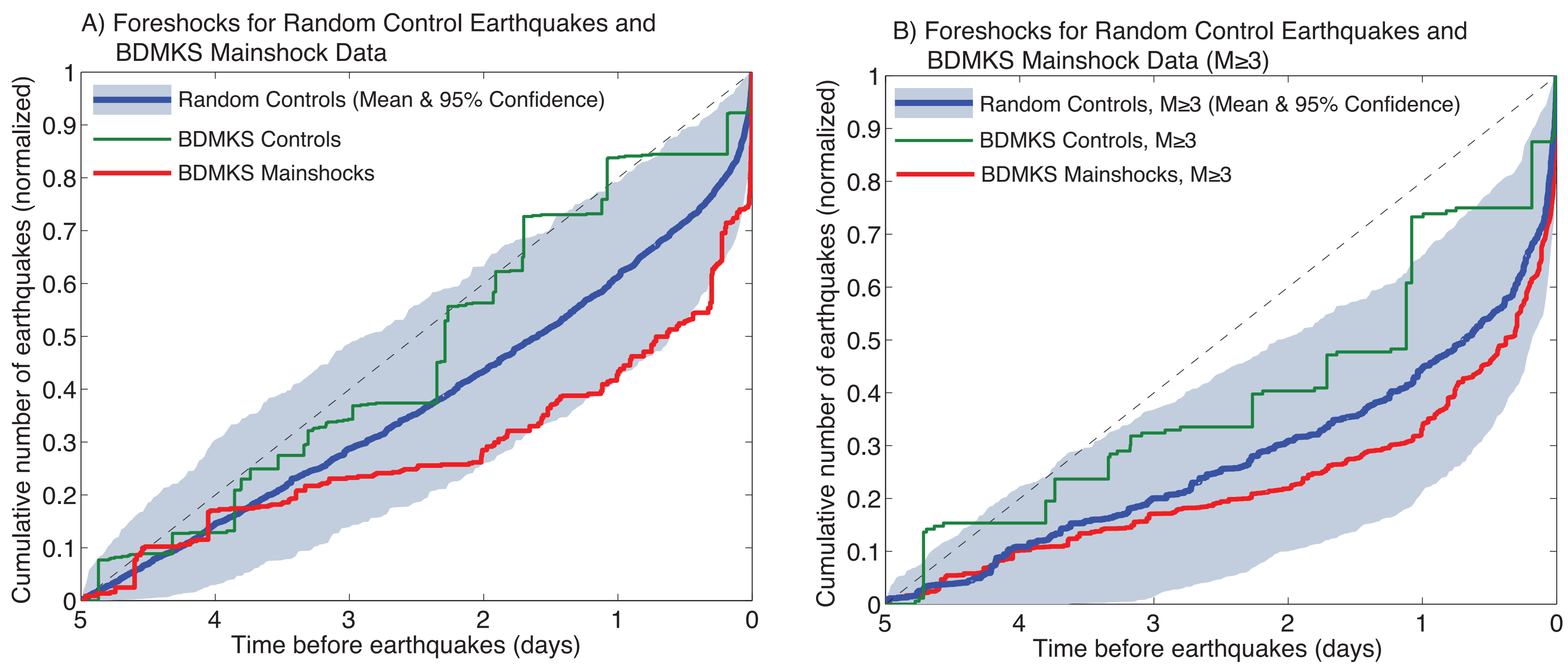
Inverse Omori Acceleration

ETAS models can match the acceleration seen in Bouchon et al. (2014) dataset



Felzer, Page and Michael (2015)

The cascade model predicts that the same amount of inverse Omori acceleration should be seen before earthquakes of any size

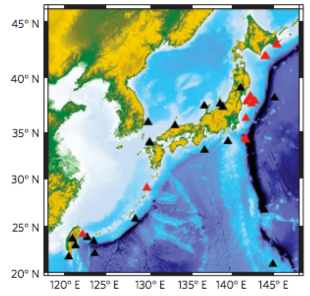


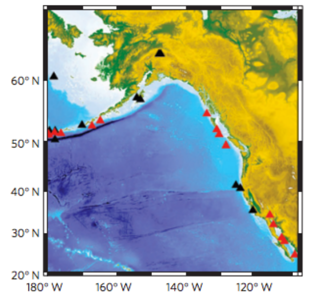
Indeed, the acceleration before small earthquakes is similar

(if you correct for completeness problems in the Bouchon et al. (2014) dataset)

Felzer, Page and Michael (2015)

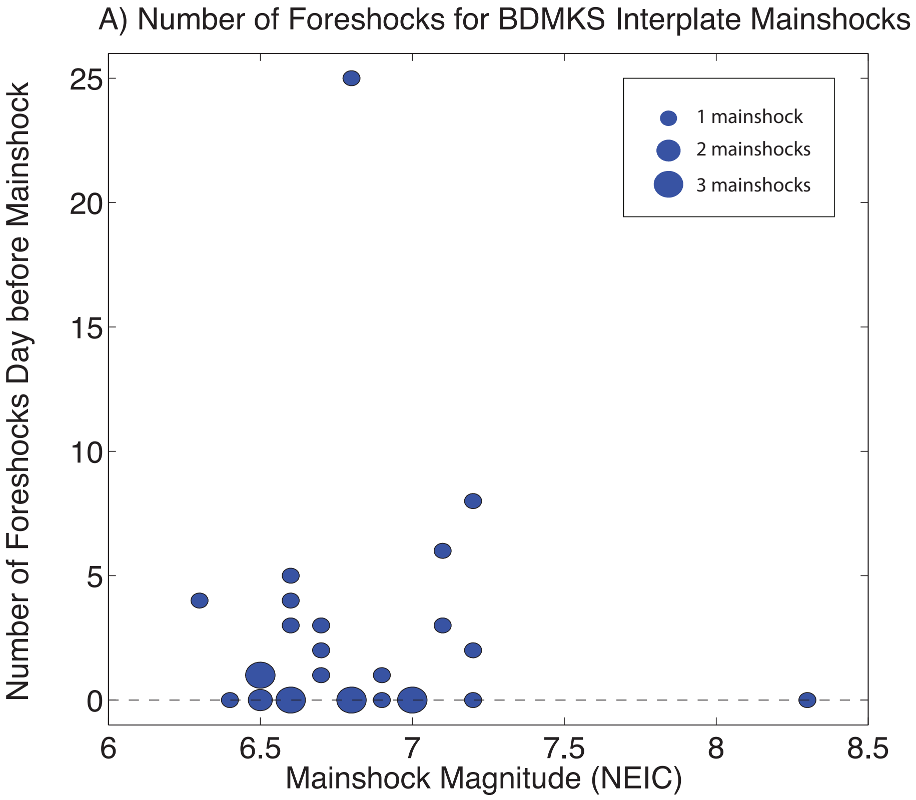
Bouchon et al. (2013) dataset

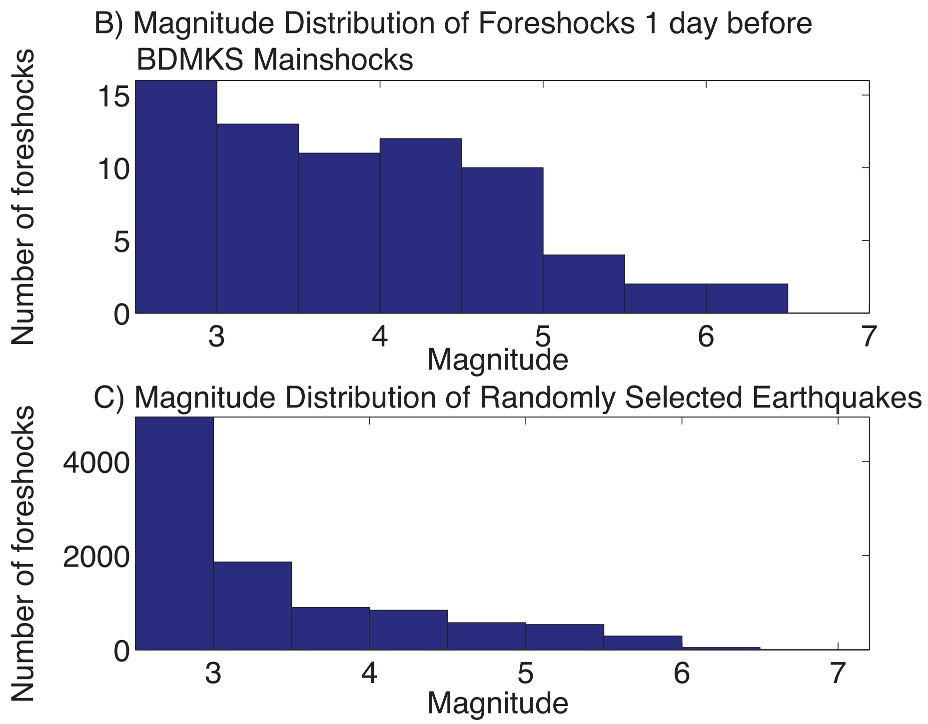




The number of foreshocks does not scale with mainshock size …

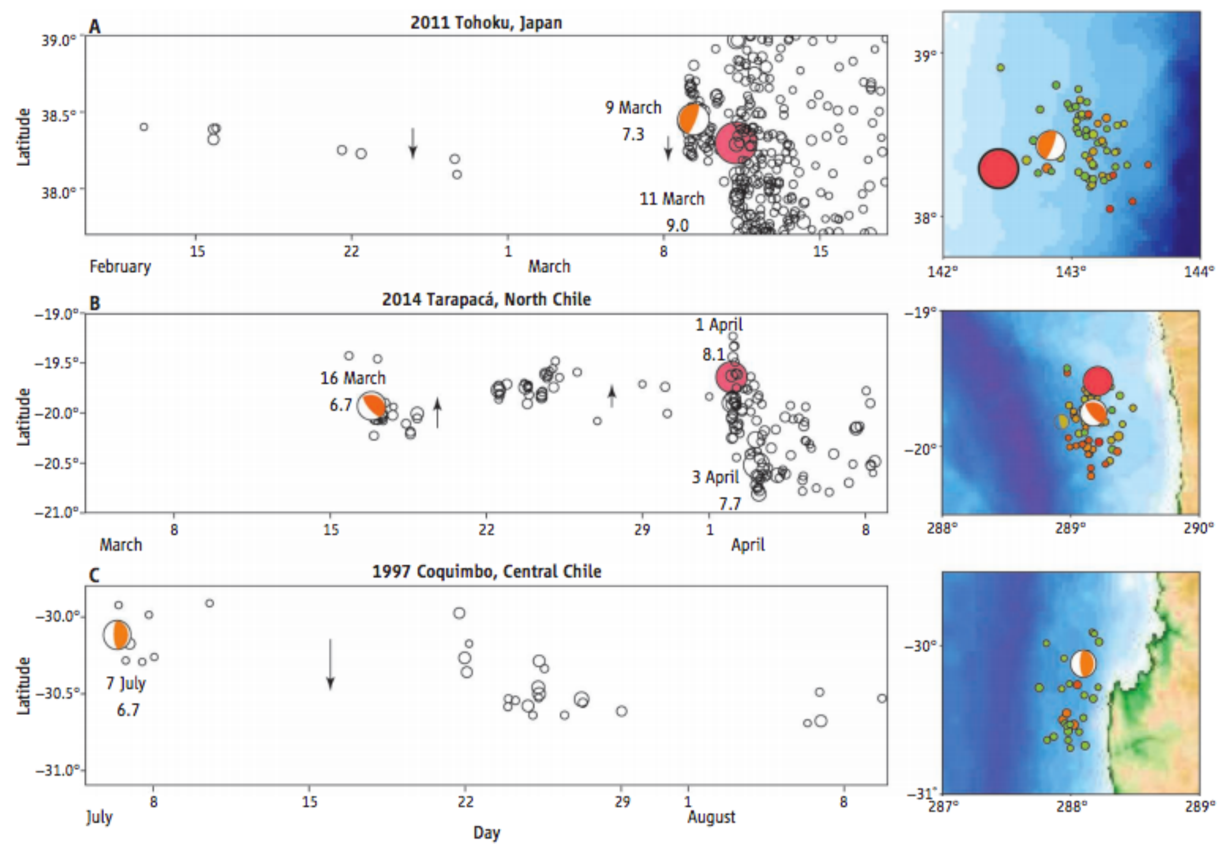
…and the foreshock magnitude distribution is approximately uniform, not G-R distributed.





Felzer, Page and Michael (2015)

Slow slip & seismicity migration may indeed happen, but does that imply predictability for mainshock size?



Brodsky and Lay (2014)

A wealth of data supporting foreshock scaling laws suggests no.

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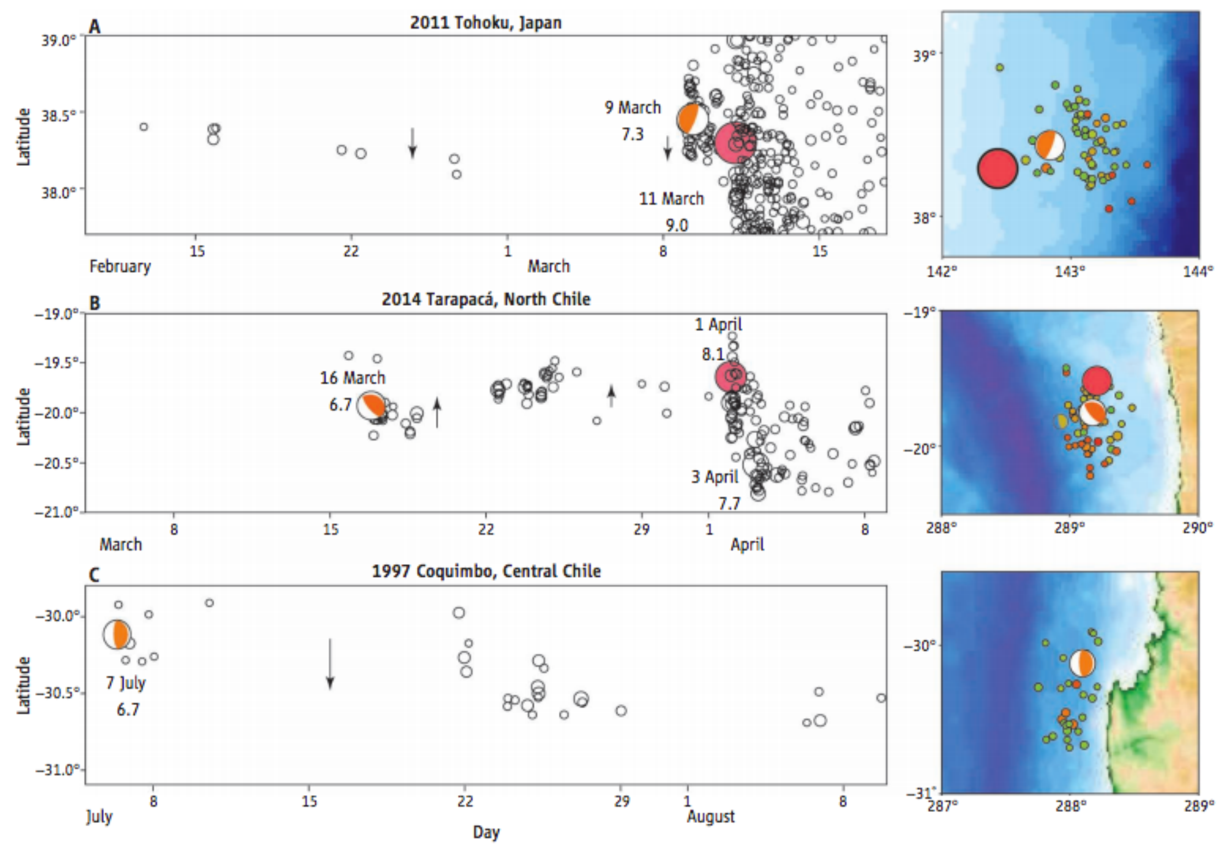


Brodsky and Lay (2014)

A wealth of data supporting foreshock scaling laws suggests no.

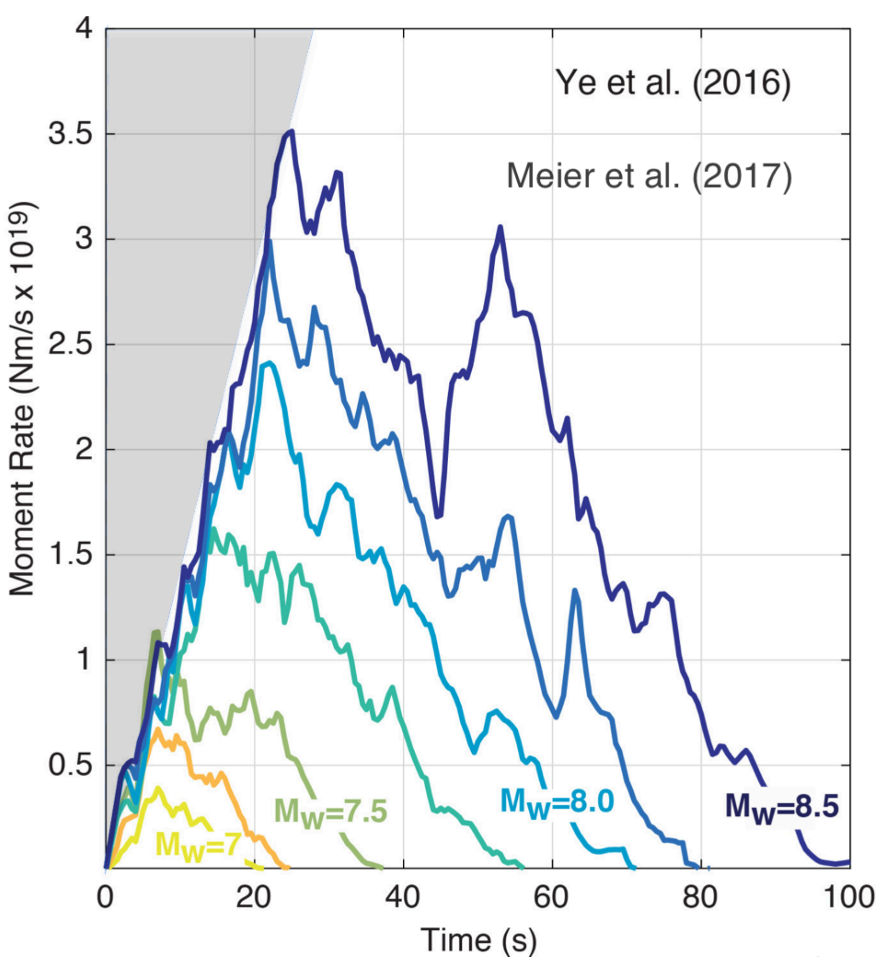
Foreshocks do contain predictive power, but not about the size of the mainshock.

Foreshocks are not predictive of mainshock size

Science Home News Journals Topics Careers

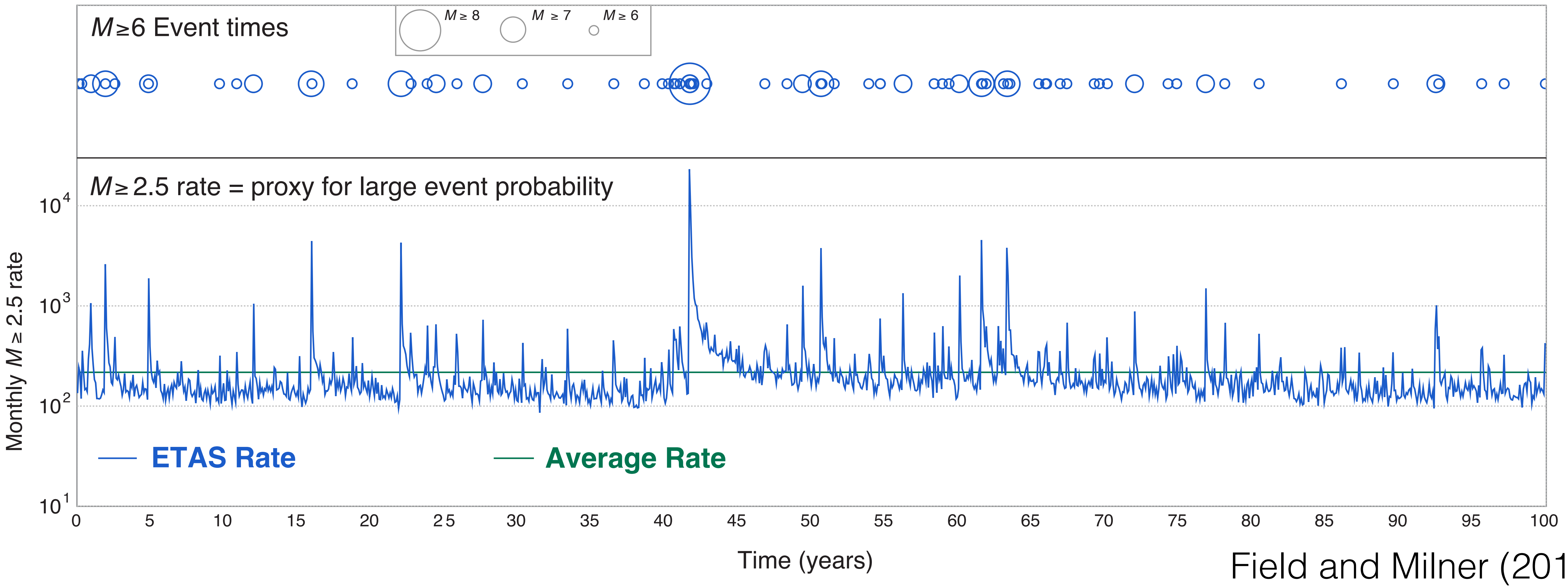
The hidden simplicity of subduction megathrust earthquakes

M.-A. Meier,* J. P. Ampuero, T. H. Heaton



Moment rate functions all start out the same, which suggests the earthquake doesn't "know" its final size

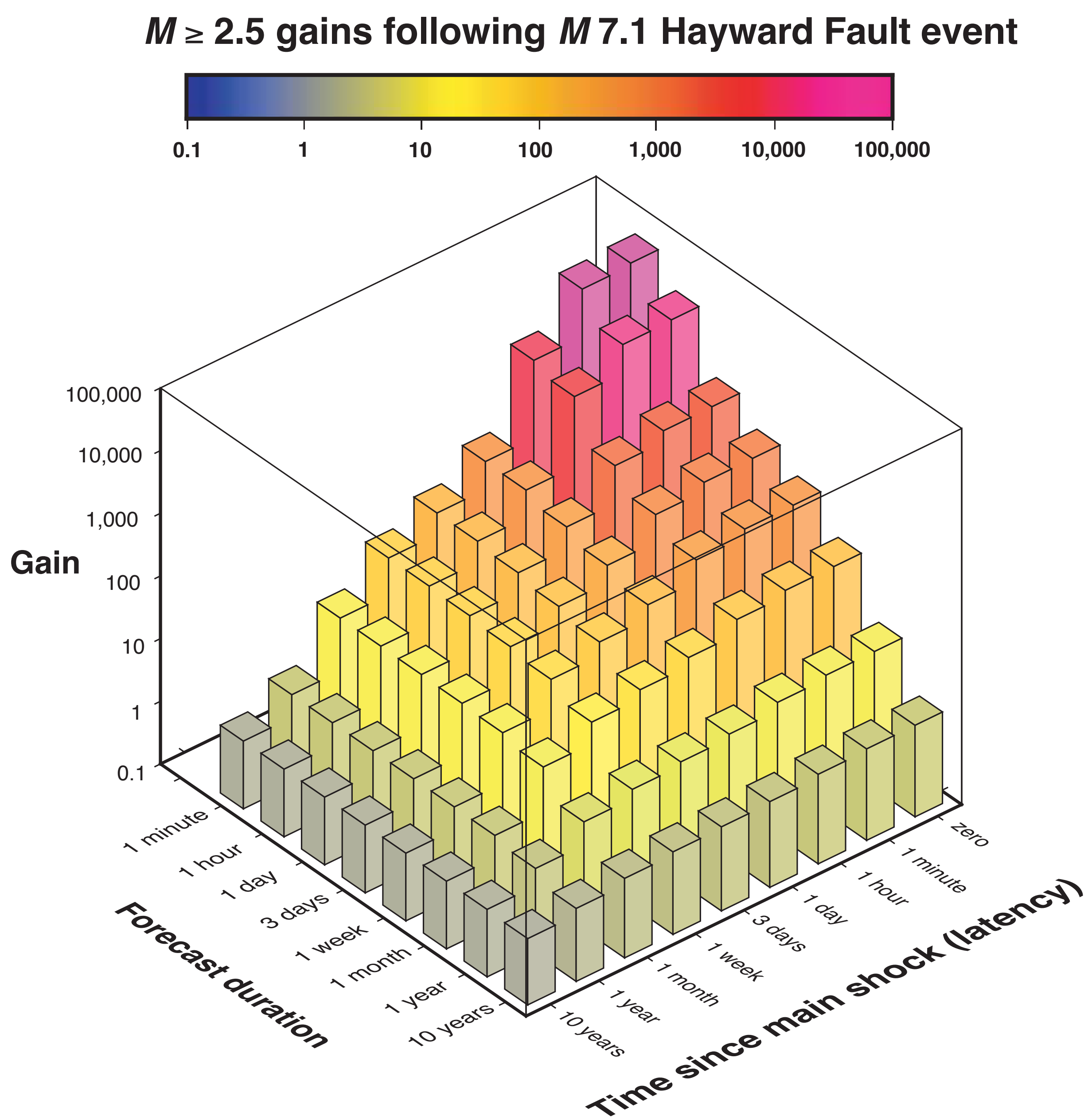
What do changing earthquake probabilities look like in time?



Field and Milner (2018)

Even though foreshocks are not predictive of earthquake size, foreshock/aftershock statistics can give orders of magnitude changes in the probabilities for future earthquakes of all sizes.

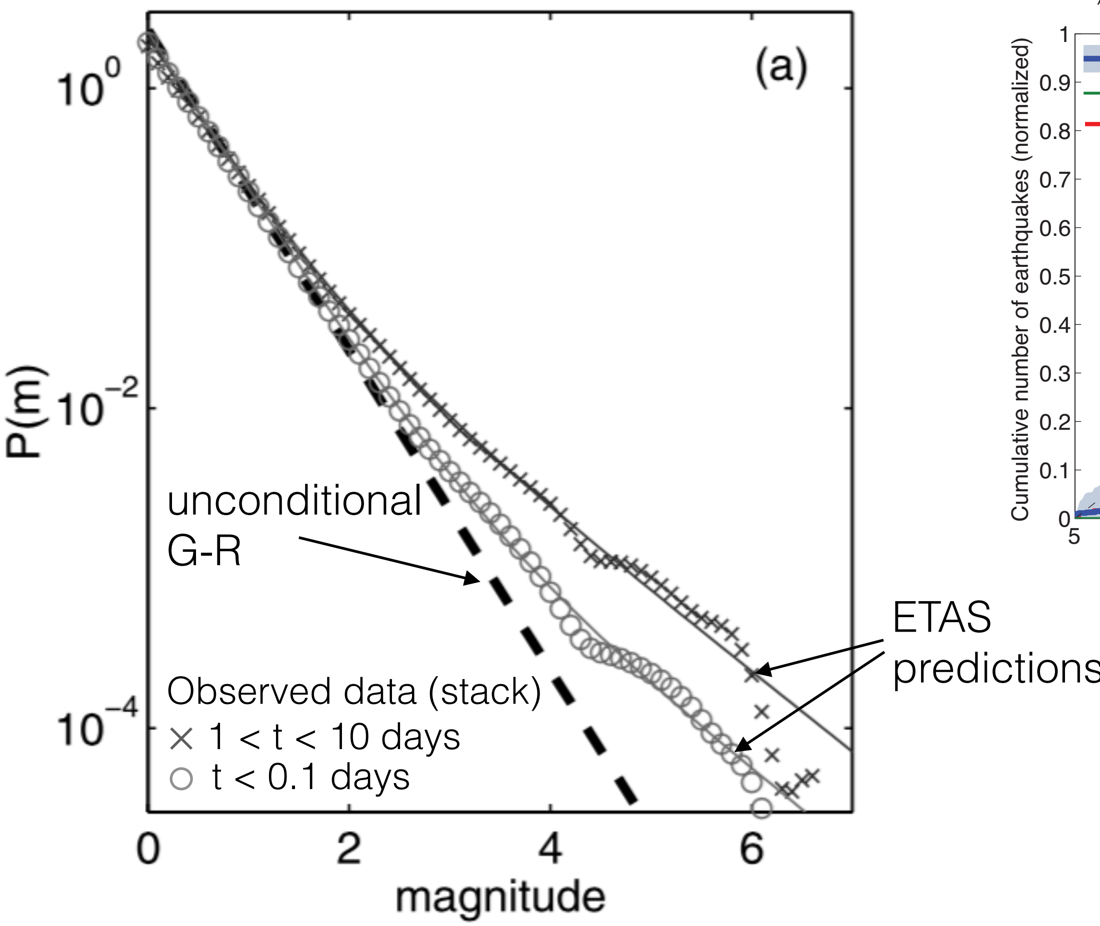
How big are the probability gains in ETAS?

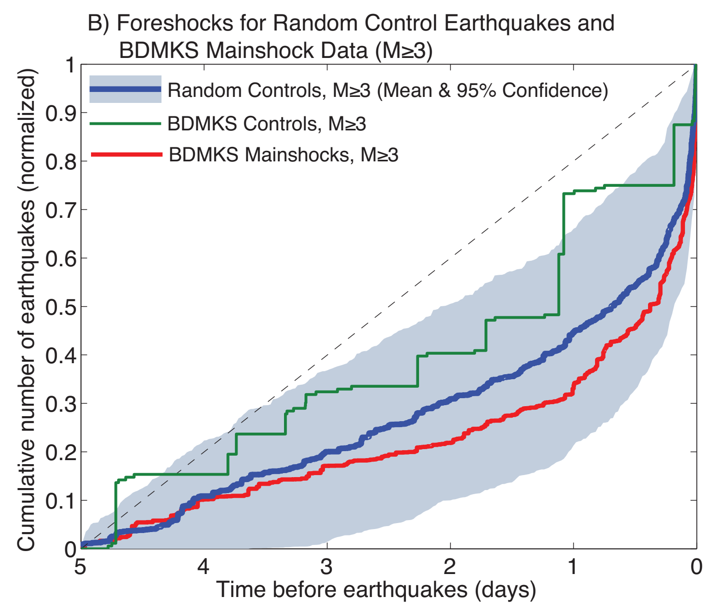


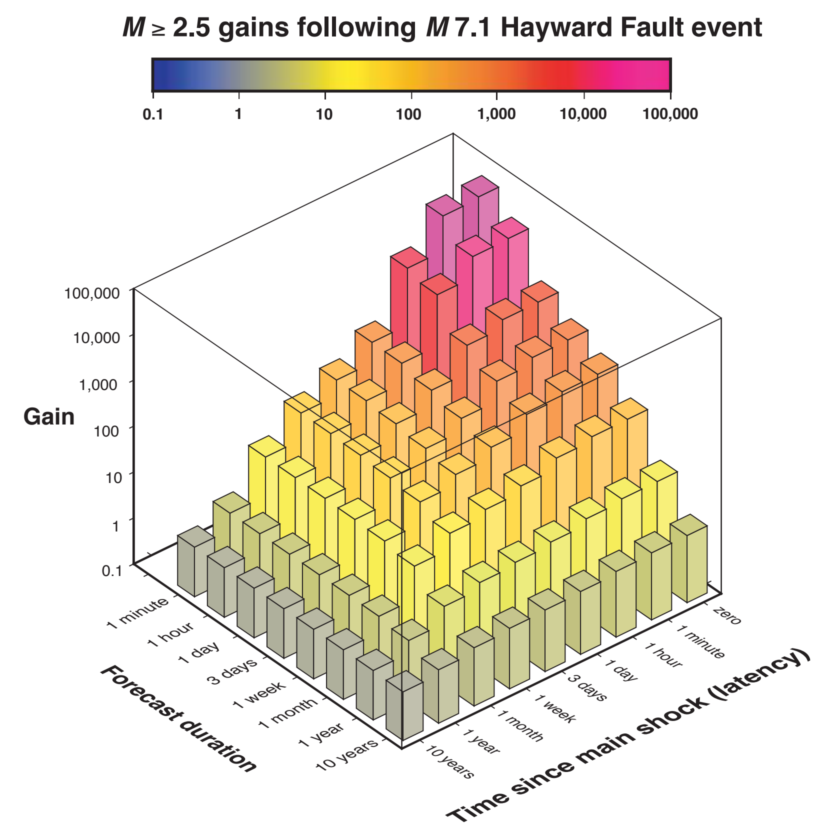
Field and Milner (2018)

Well-characterized scaling relations imply:

- b-value anomalies and inverse Omori acceleration for stacked foreshocks
- Probability gains of 100-1000 on time scales of a day







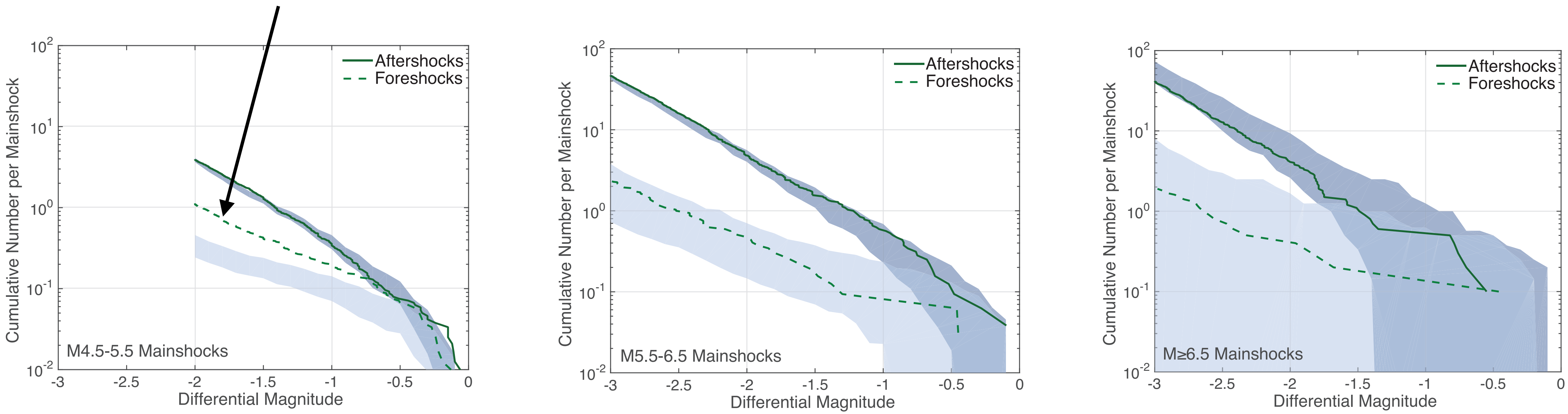
ETAS is an excellent null hypothesis that explains a large amount of the observed predictability in the data

Deviations from ETAS?

Foreshock and Aftershock Productivity as a Function of Differential Magnitude

As noticed by Brodsky (2011) and Shearer (2012), mainshocks in California have twice as many foreshocks as ETAS prediction

But this effect is only seen for smaller mainshocks!



Green lines show 28-year observed catalog in California
Blue shaded regions show range from 28-year UCERF3-ETAS snapshots

Page and van der Elst (2018)

Deviations from ETAS?

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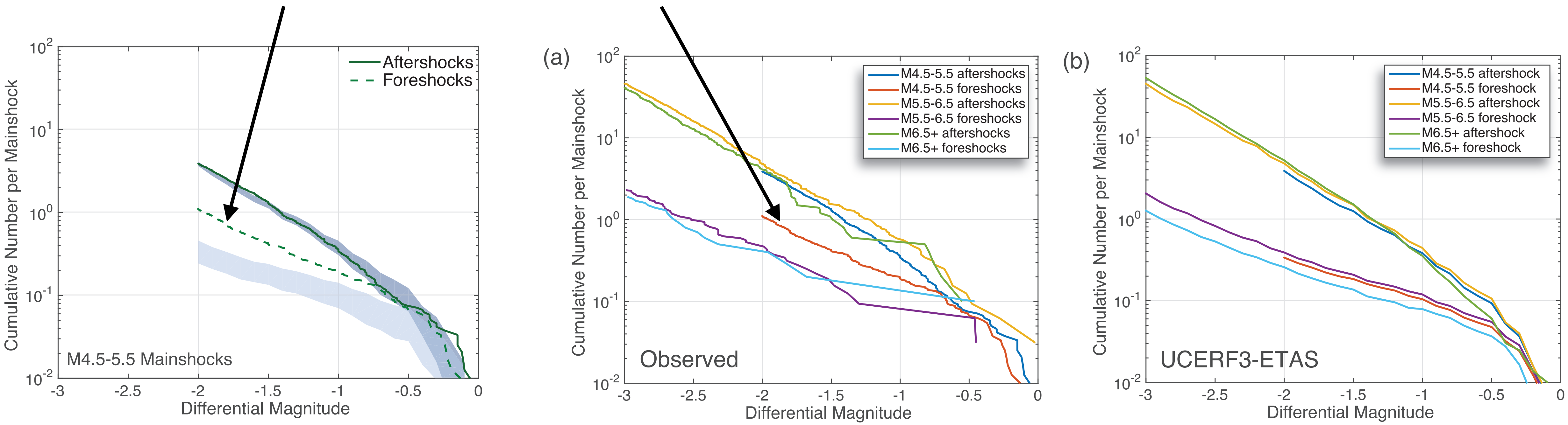
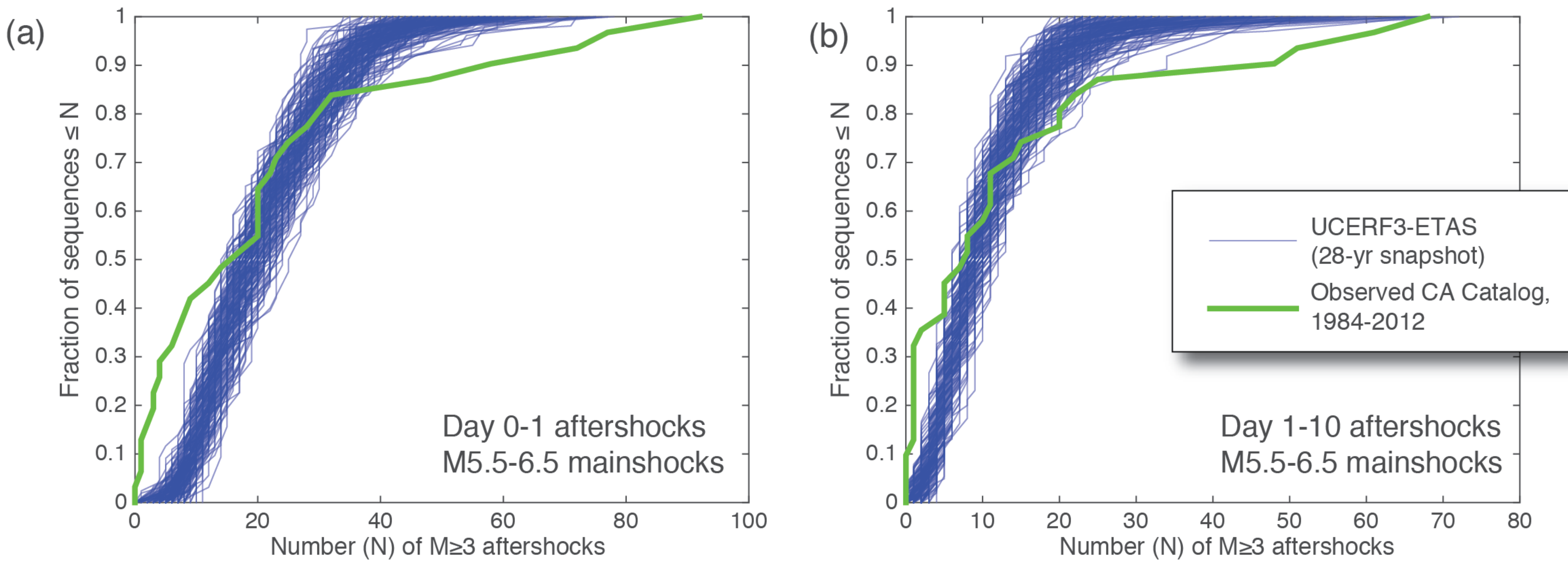


Page and van der Elst (2018)

Deviations from ETAS?

Inter-sequence Aftershock Productivity Variability



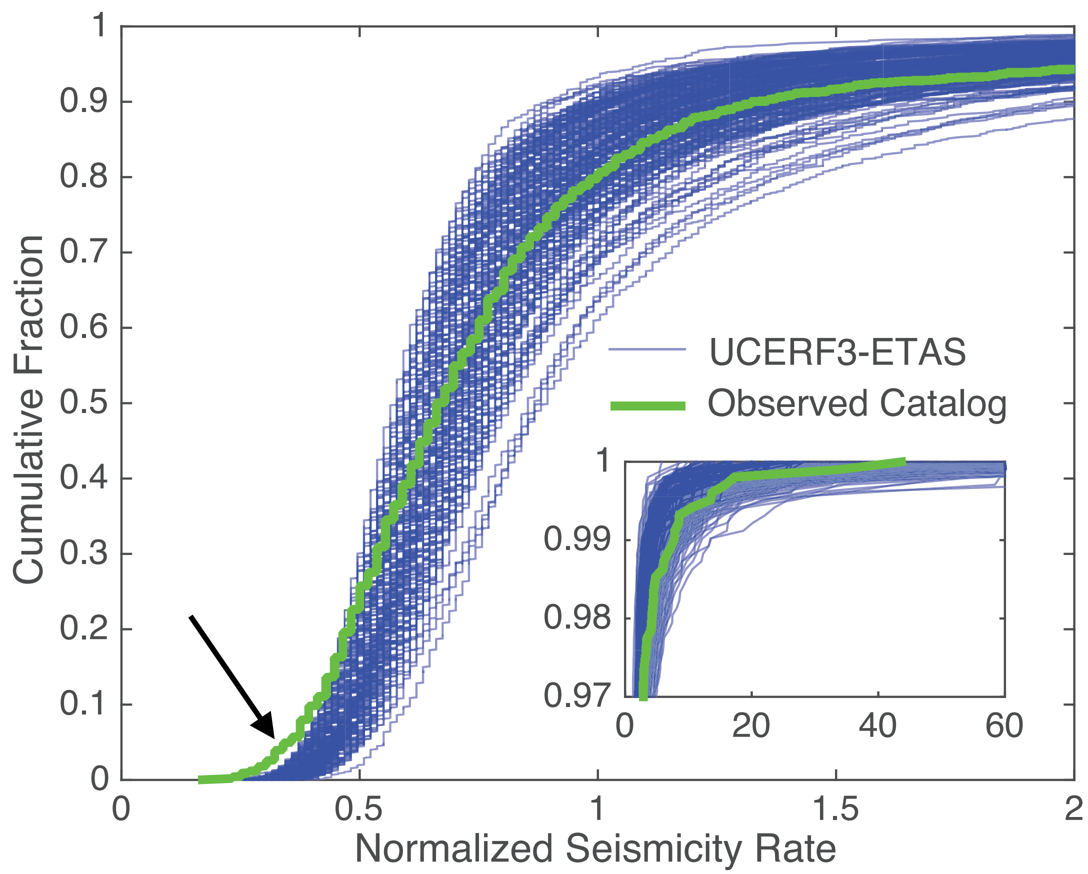
ETAS models that use one set of direct Omori parameters have less aftershock productivity variability than observed catalog

Page and van der Elst (2018)

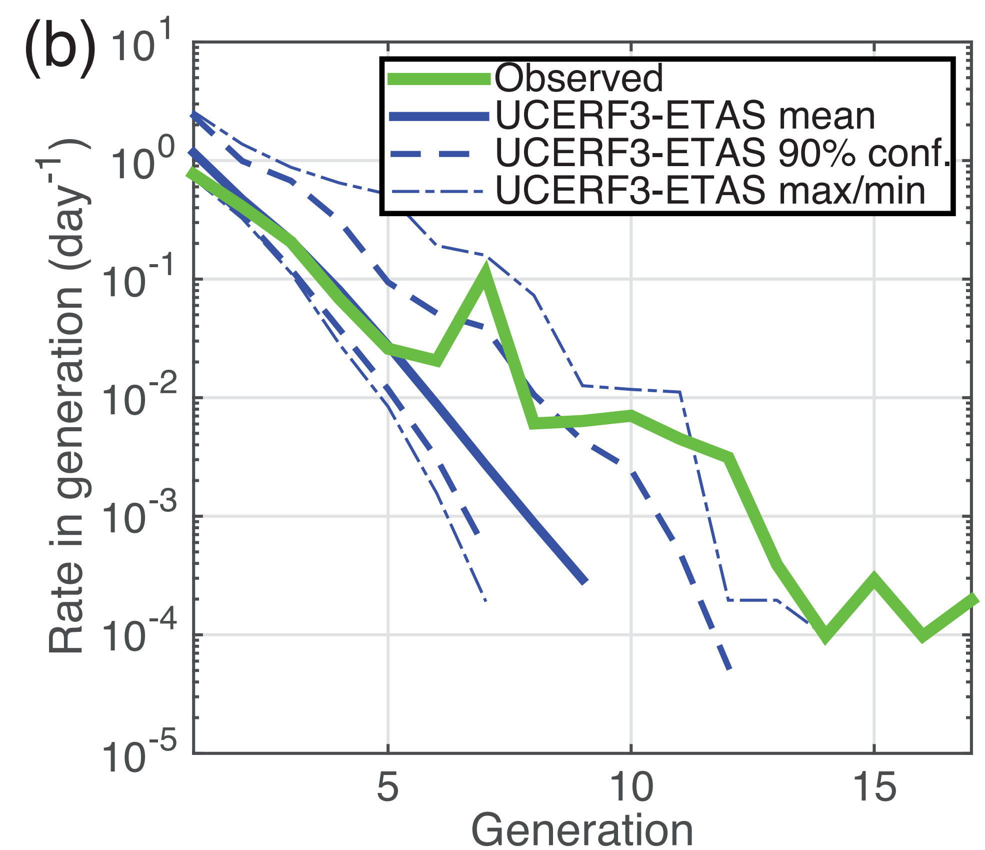
Deviations from ETAS?

Direct Omori parameters are likely close to critical (very little "background")

Including the effect of "orphaned" aftershocks is important



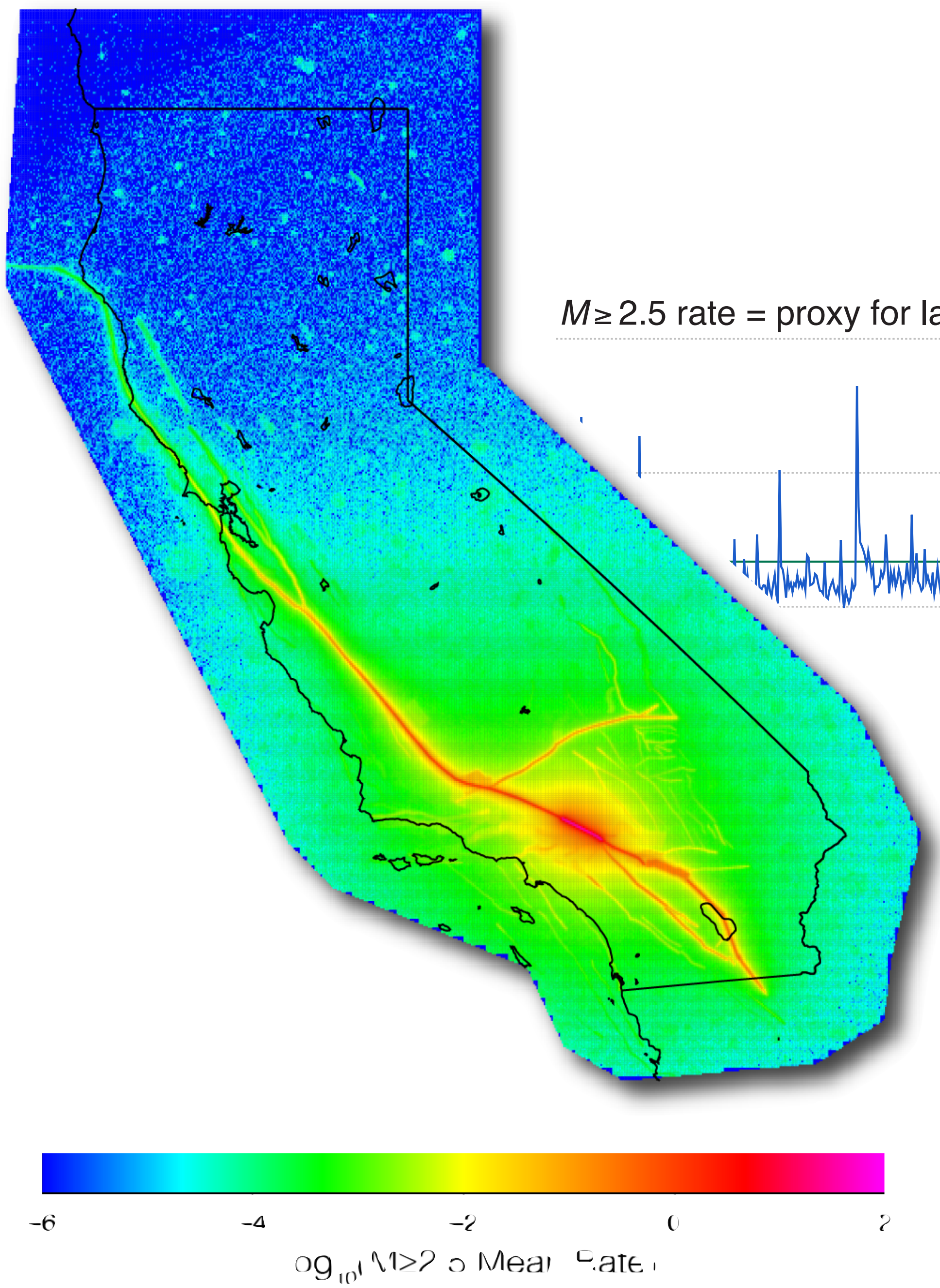
Real catalog (green) has more quiet periods

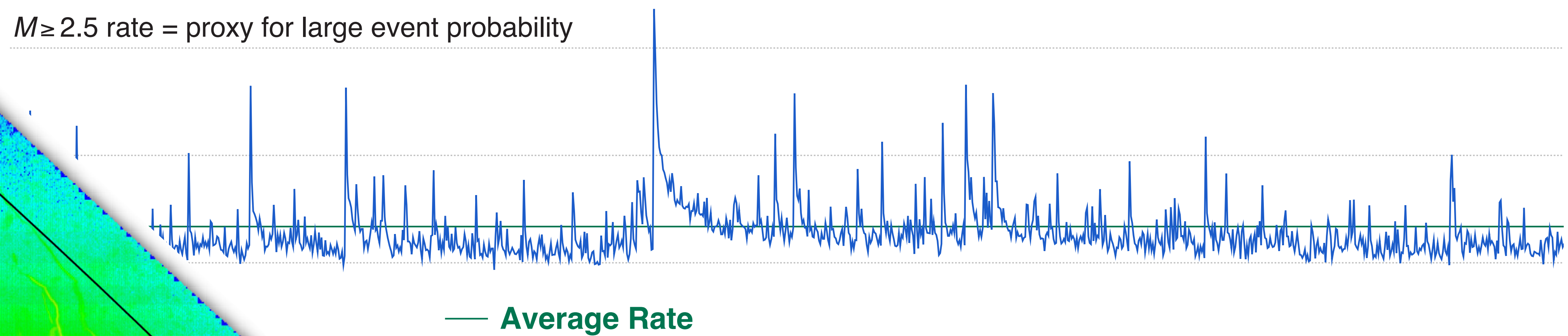


Real catalog (green) has more sequences that extend to higher generations

Page and van der Elst (2018)

ETAS captures much of the predictability in seismicity





By better estimating parameters & modeling variations, we can further increase probability gains