Limitations of Earthquake Triggering Models*

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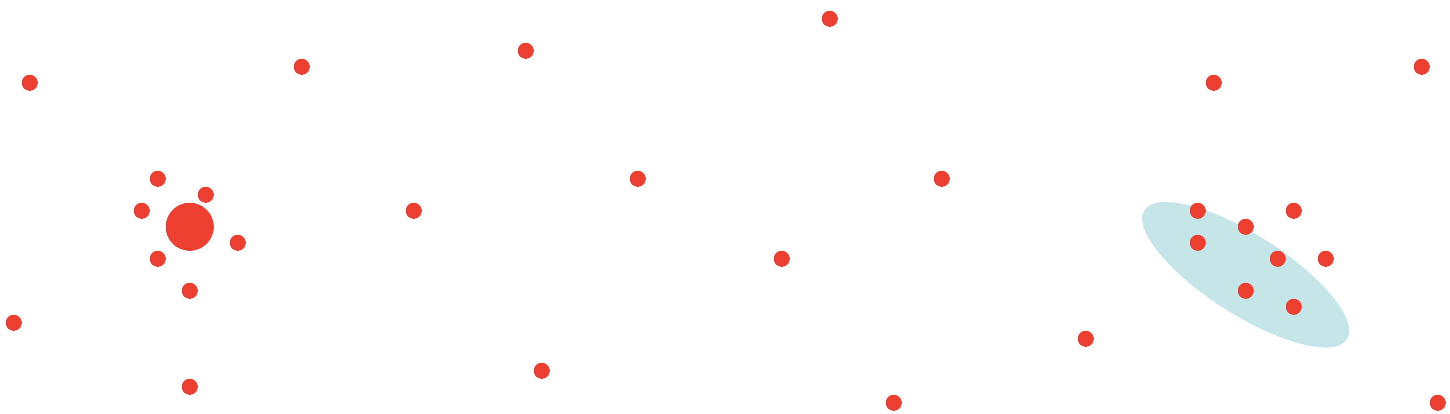
* in Southern California

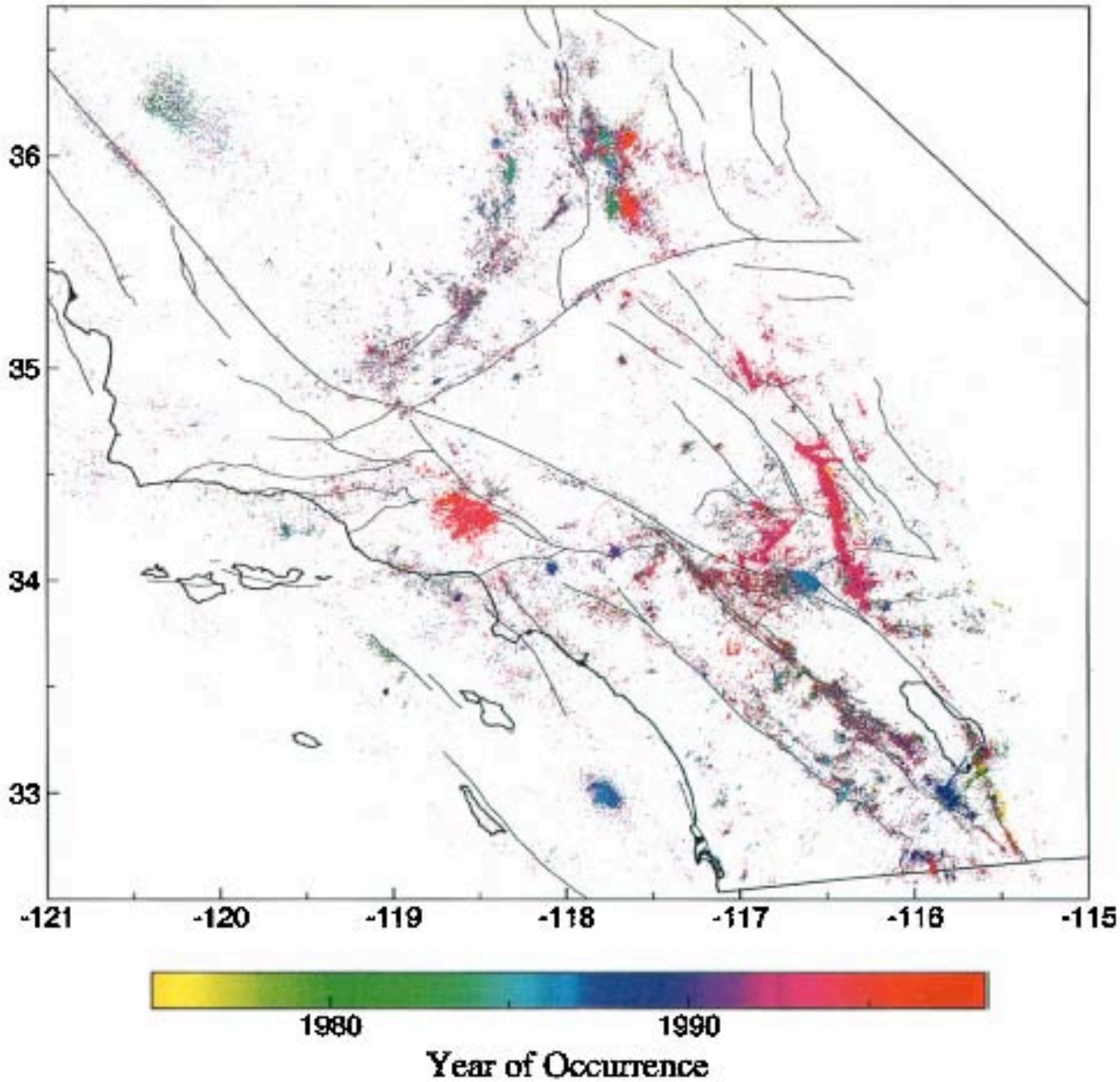
Why do earthquakes cluster in time and space?

- Earthquake triggering. Event A increases probability of future nearby events. Very clear in aftershock sequences, although mechanism (static vs. dynamic triggering) is debated.

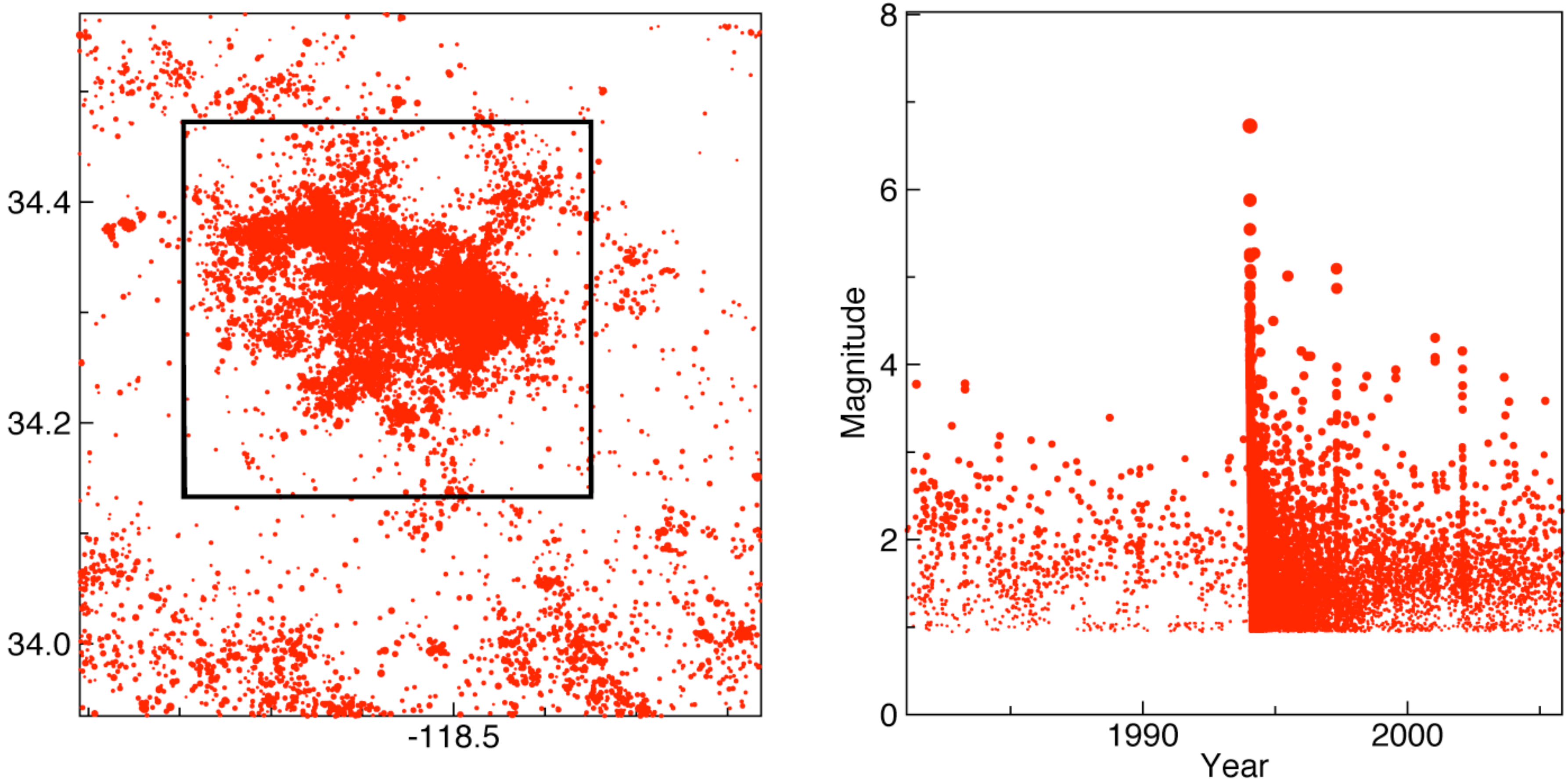
- Underlying physical changes, such as slow creep, pore fluid pressure variations, etc. Often invoked to explain earthquake swarms.



Southern California Seismicity

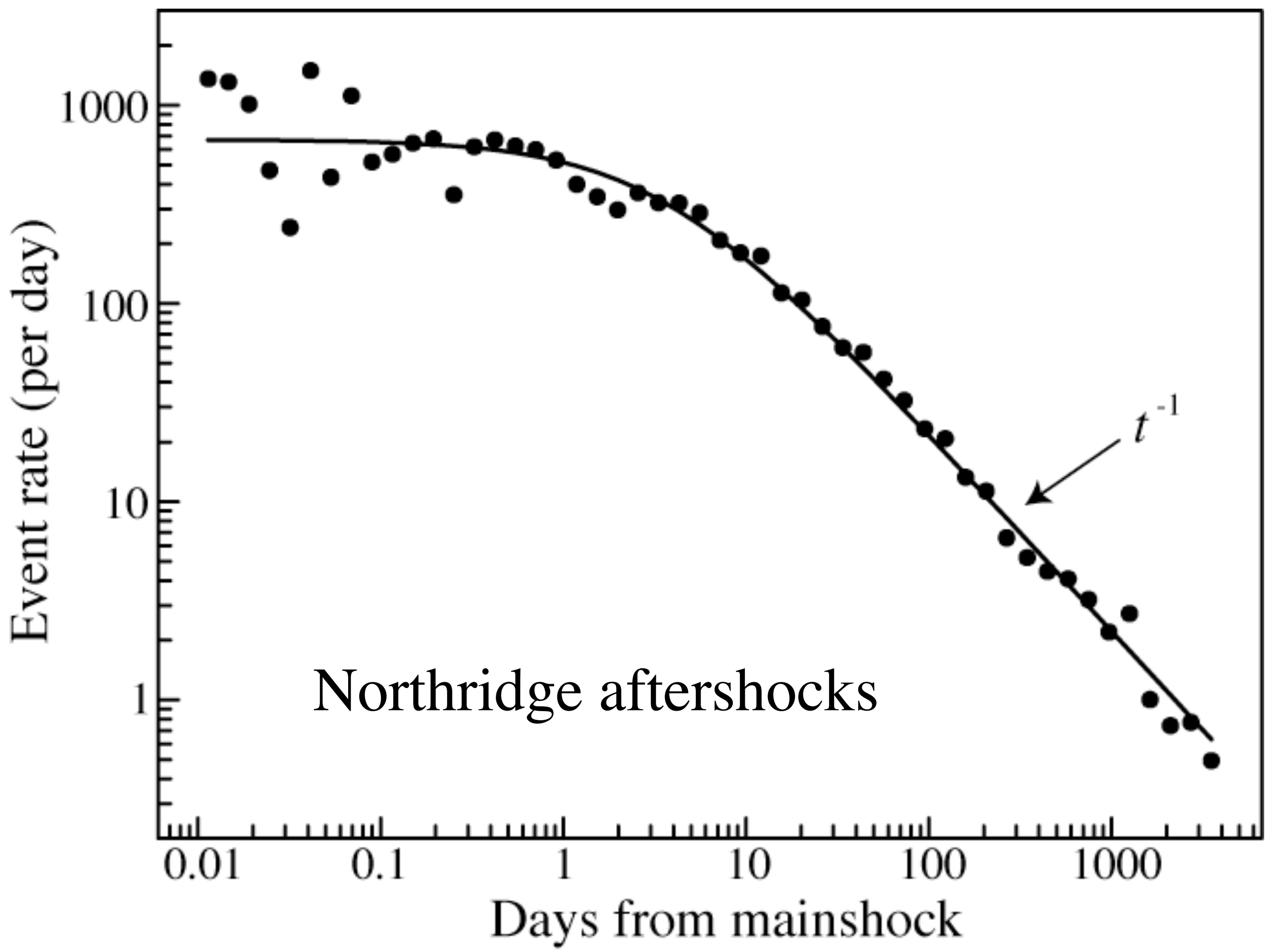


1994 Northridge Earthquake (M 6.7)

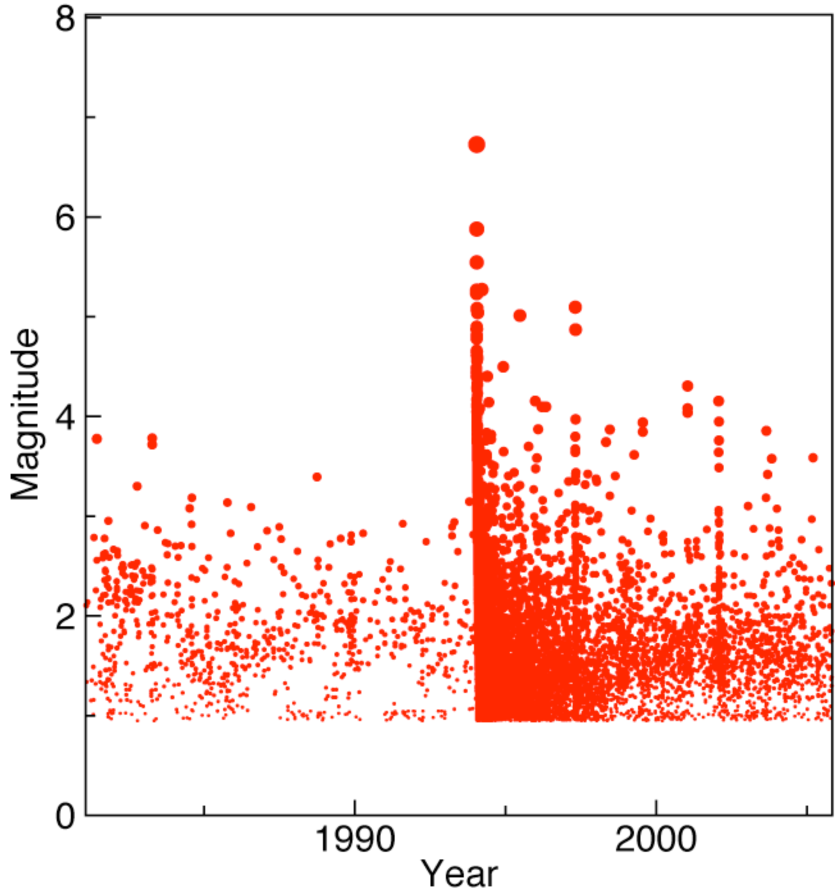


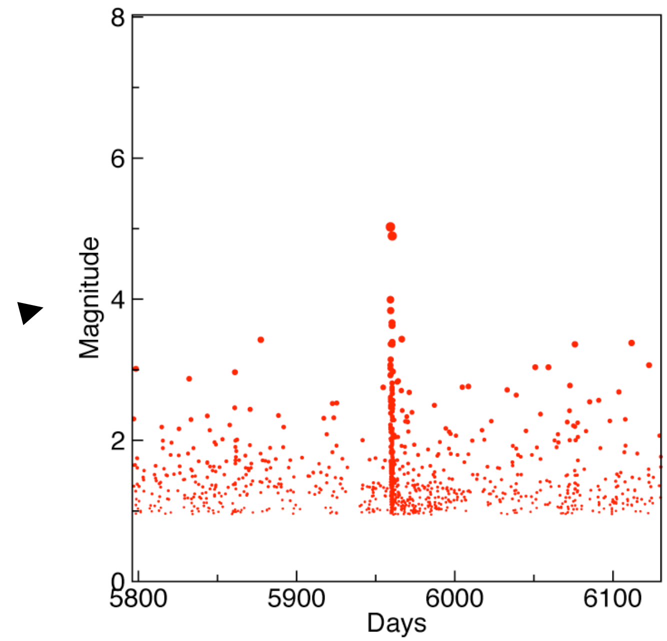
Omori's Law (Omori, 1894)

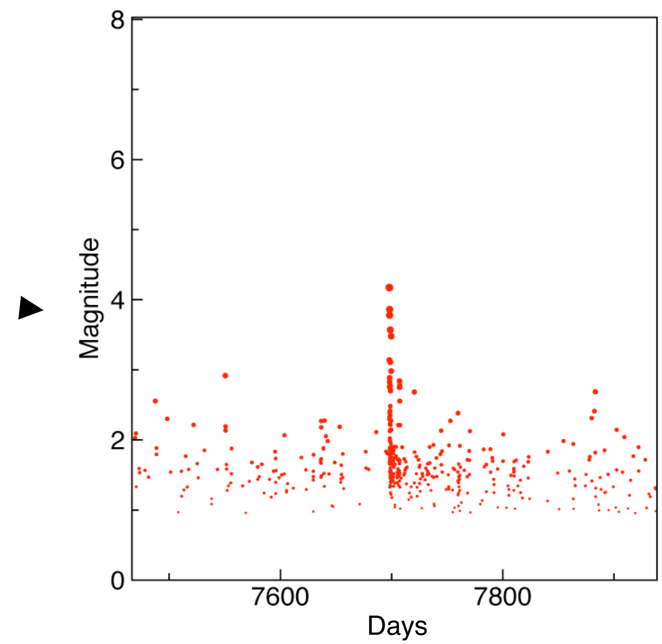
$$n(t) = K(t + c)^{-1}$$



Secondary aftershocks



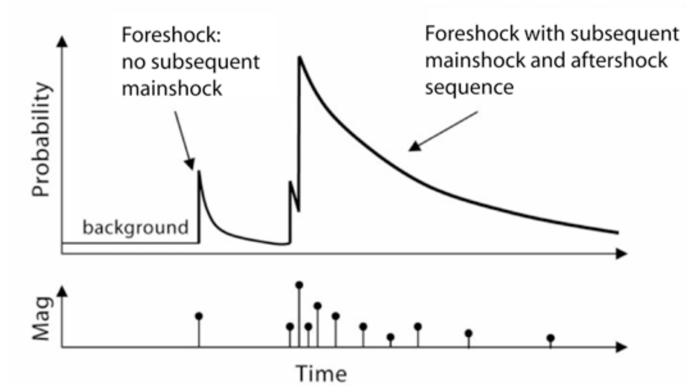




Epidemic Type Aftershock Sequences (ETAS) modeling

predicted rate
background rate
sum over previous events
mainshock size dependence
Omori's Law
distance dependence

$$\lambda(\mathbf{x},t) = \lambda_0 + \sum_i \kappa 10^{\alpha(m_i - m_0)} (t_i + c)^{-p} r_i^{-q}$$



where:

$\lambda(\mathbf{x},t)$ = predicted event density

λ_0 = background rate (untriggered)

κ = triggering productivity parameter

m_i = magnitude of each earthquake

m_0 = minimum magnitude of the counted events

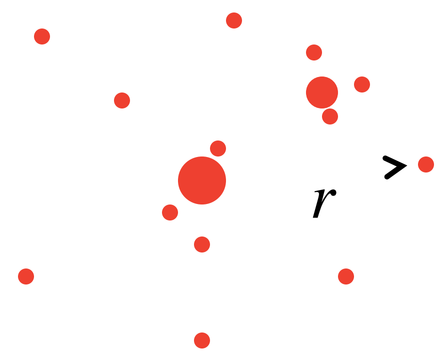
$\alpha \approx 1$ (larger earthquakes trigger more events)

t_i = time from the ith event to t

c and p (≈ 1) are the Omori decay constants

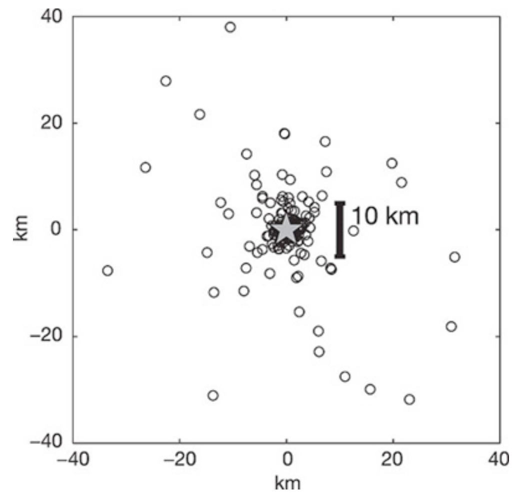
r_i = distance from the ith event to $\mathbf{x}$

q defines the decay with distance

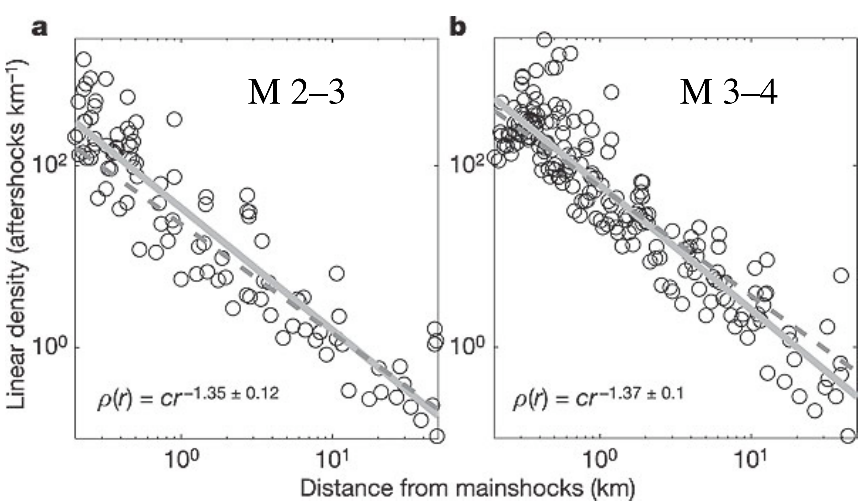


Aftershock distance dependence (*Felzer & Brodsky*, 2006)

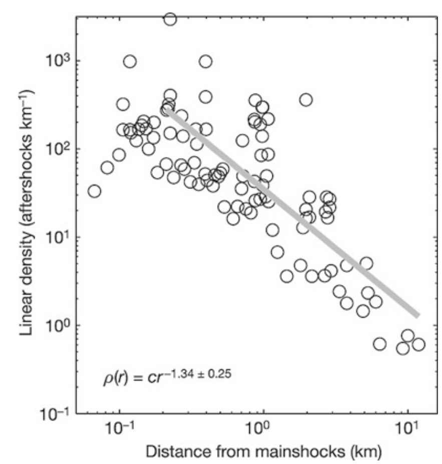
- Used relocated southern California catalog
- Stacked "mainshocks" to get average aftershock densities
- Results suggest $q \sim 3.3$ in r^{-q} dependence of aftershocks on distance



30 minutes after 2,355 M 3–4 mainshocks



5 minutes after 7,396 M 2–3 and 2,355 M 3–4 mainshocks



2 days after 9 M 5–6 mainshocks

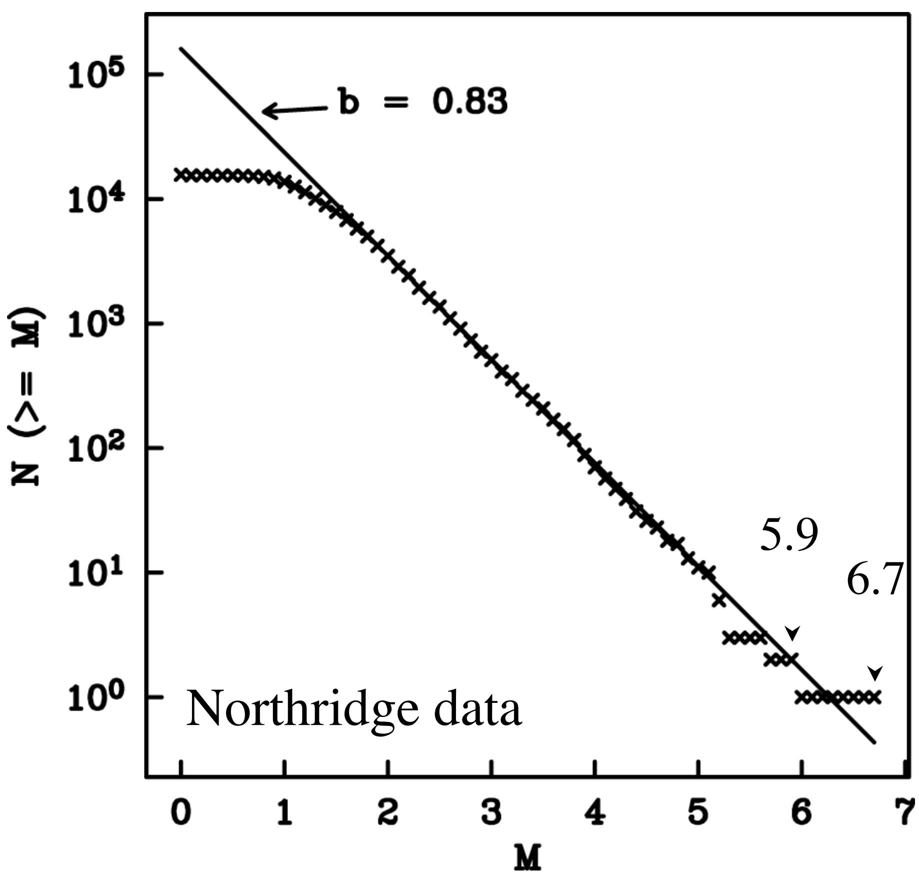
(no photo on web)

Emily Brodsky

Gutenberg-Richter relation

$$\log_{10} N = a - bM$$

b value, generally observed to be 0.8 to 1.2

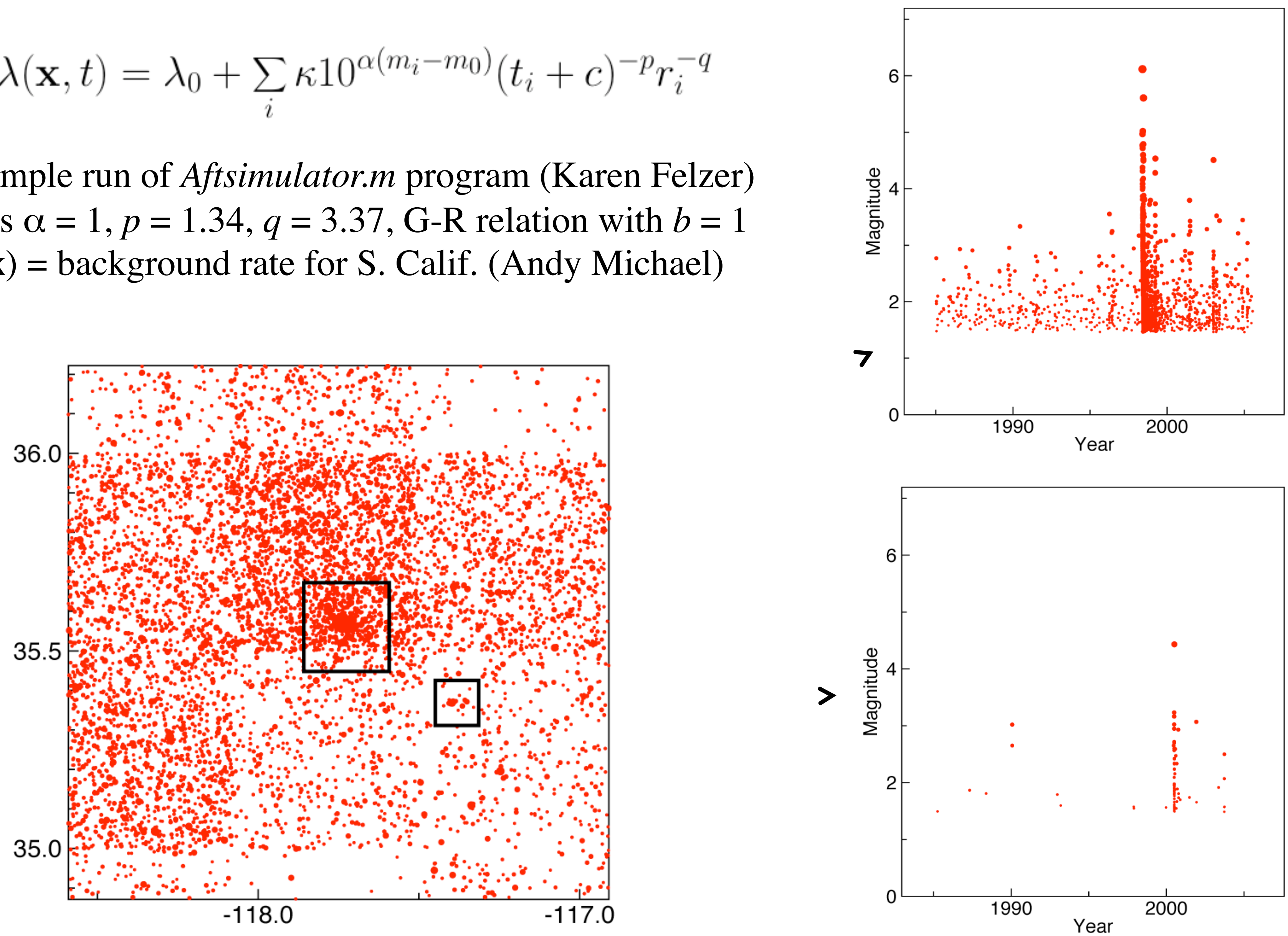


productivity parameter (for aftershock sequences, *a* can be estimated from: *Bath's Law: the largest aftershock is about one magnitude smaller than the mainshock*)

Simulated catalog

$$\lambda(\mathbf{x}, t) = \lambda_0 + \sum_i \kappa 10^{\alpha(m_i - m_0)} (t_i + c)^{-p} r_i^{-q}$$

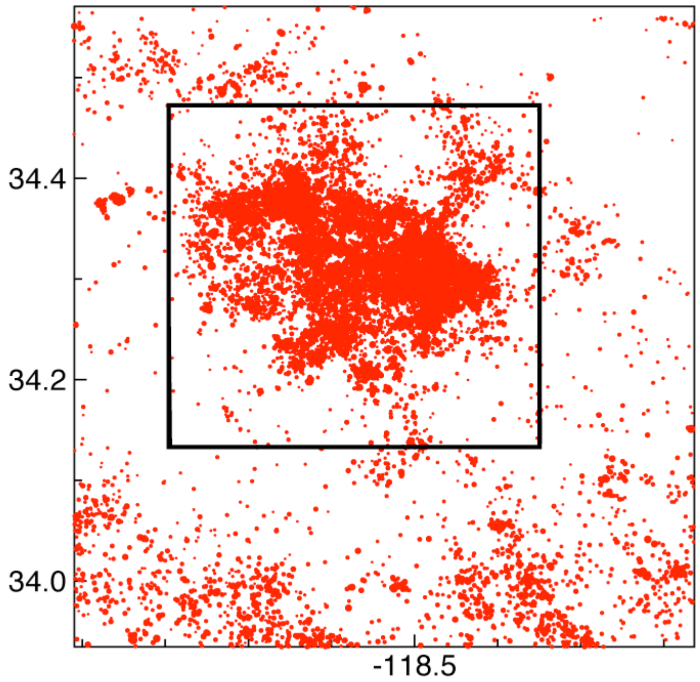
Example run of *Aftsimulator.m* program (Karen Felzer)
Uses $\alpha = 1$, $p = 1.34$, $q = 3.37$, G-R relation with $b = 1$
$\lambda_0(\mathbf{x})$ = background rate for S. Calif. (Andy Michael)

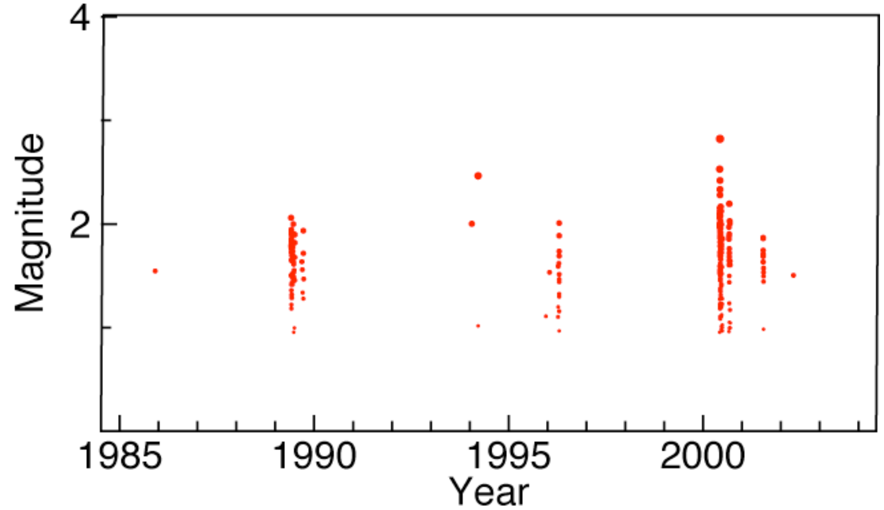


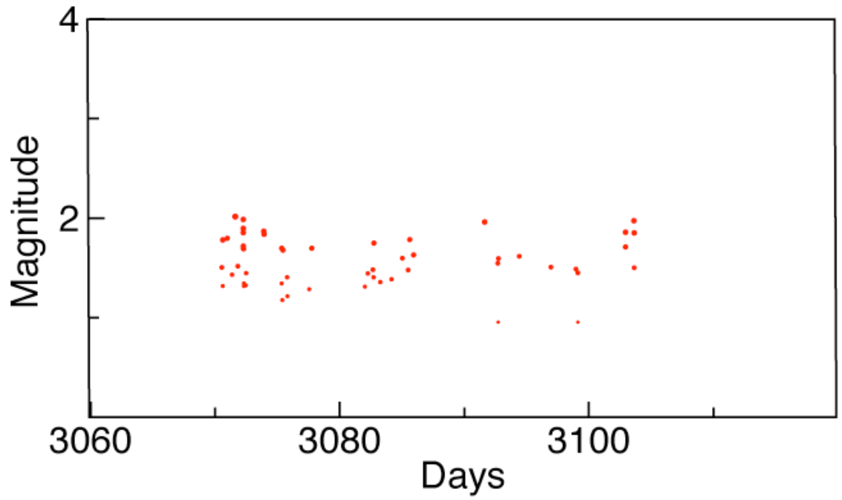
What features of real catalogs do ETAS-type models miss?

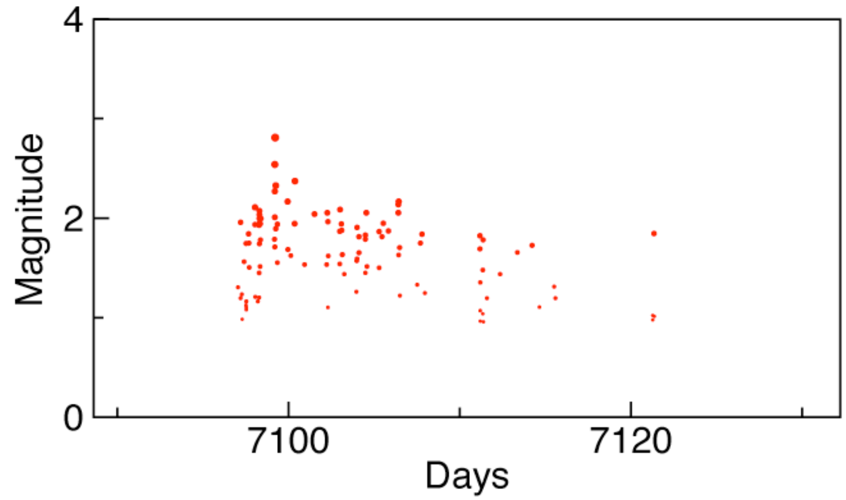
- Swarms and swarm-like behavior
- Differences in precursory activity between target events of different sizes
- Time-symmetric time/space clustering of small earthquakes

Swarms near Northridge



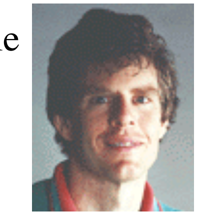






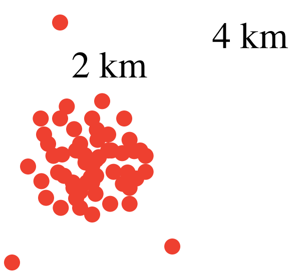
Southern California earthquake “bursts”

John Vidale

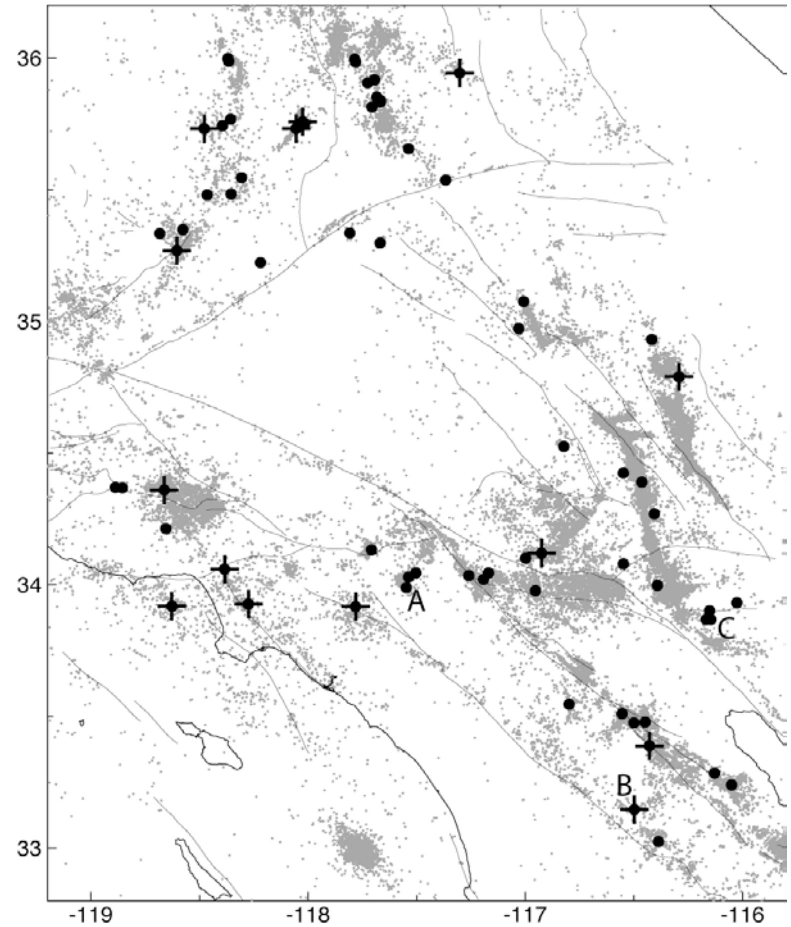


Selection criteria:

- 40 events within 2 km radius in 28 days
- fewer than 4 events in prior 28 days
- no more than 20% additional events between 2 and 4 km radius



from *Vidale & Shearer* (2006)



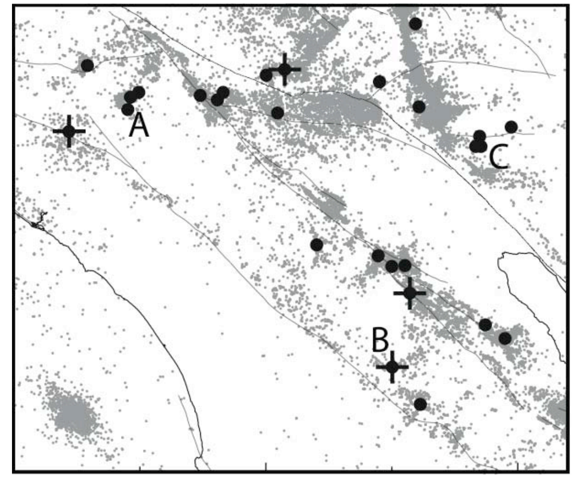
✢ 14 start with largest event (mainshock-like)

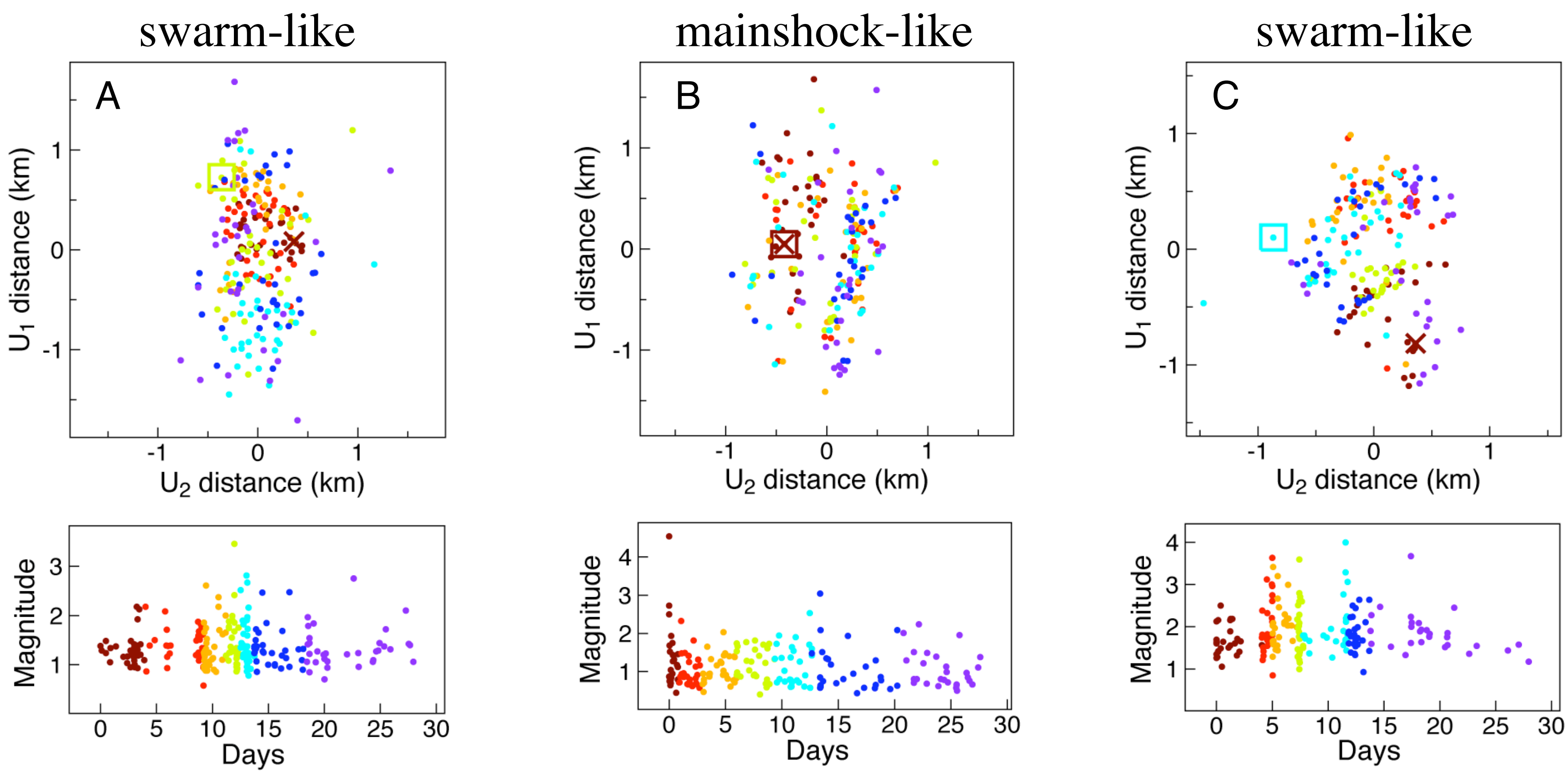
• 57 start with smaller event (swarm-like)

Southern California bursts

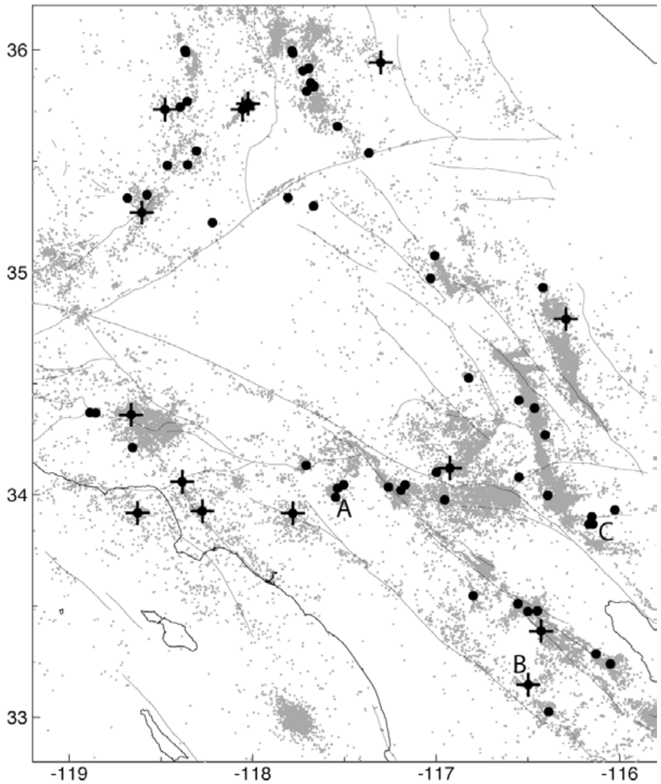
X first event

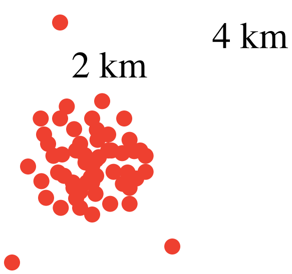
largest event





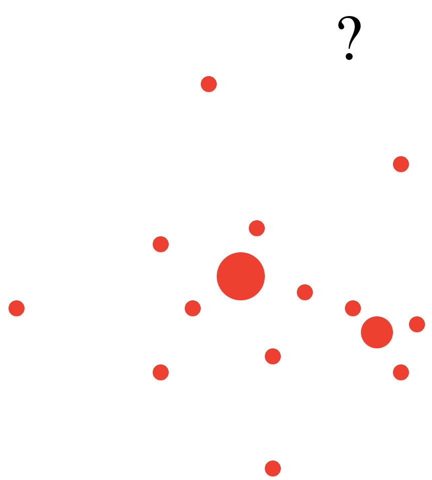
Swarm-like behavior: Evidence against simple triggering cascade





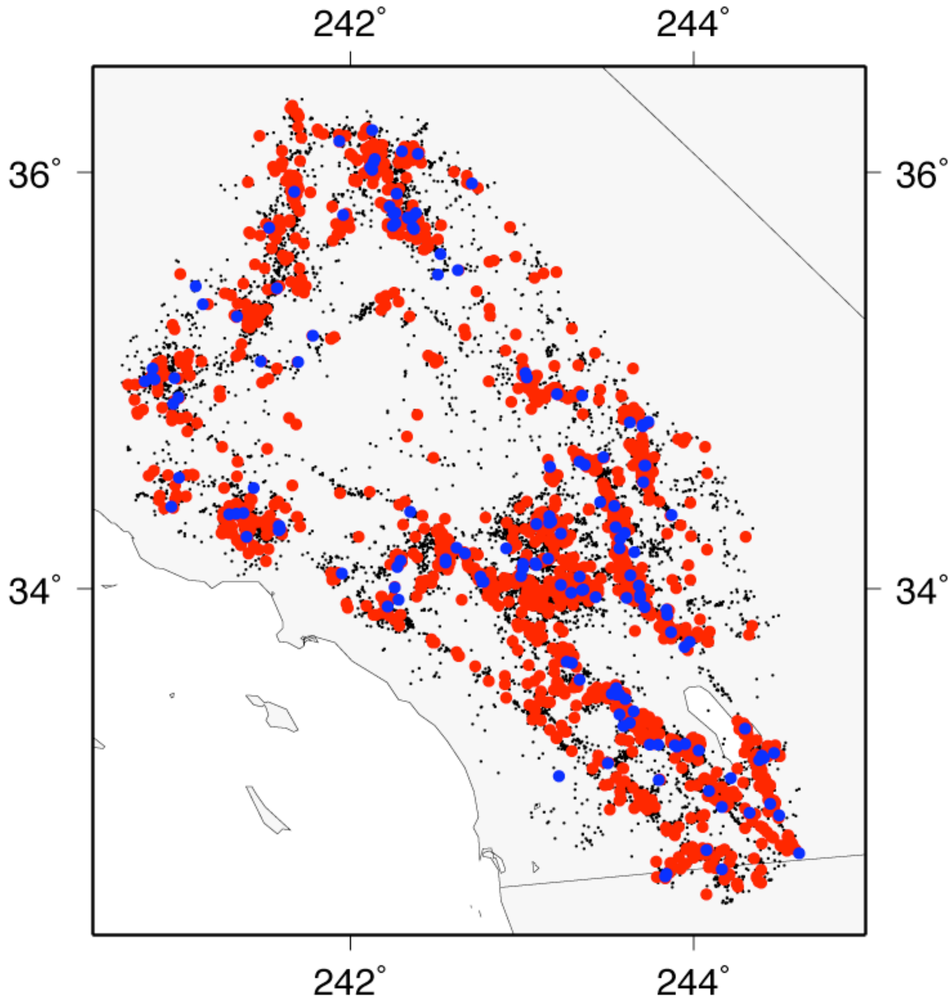
- Interval of steady seismicity rate
- Tendency for largest event to strike later in sequence
- Large spatial extent of swarms compared to their cumulative moment
- Often involve spatial migration of seismicity
- Weak correlation between number of events and magnitude of largest events
- Suggested underlying physical cause, such as pore fluid pressure changes and/or aseismic slip
- Swarms are distributed across region, not restricted to volcanic or geothermal areas

ETAS-like models predict triggered earthquakes have random sizes



- Triggering model provides probability of earthquake in this space/time box, given the past history of seismicity
- But if an earthquake occurs, its size is randomly drawn from the G-R relation
- Thus, the average precursory seismicity behavior should be identical before earthquakes of any given size

Test using LSH catalog (Lin et al., 2007)

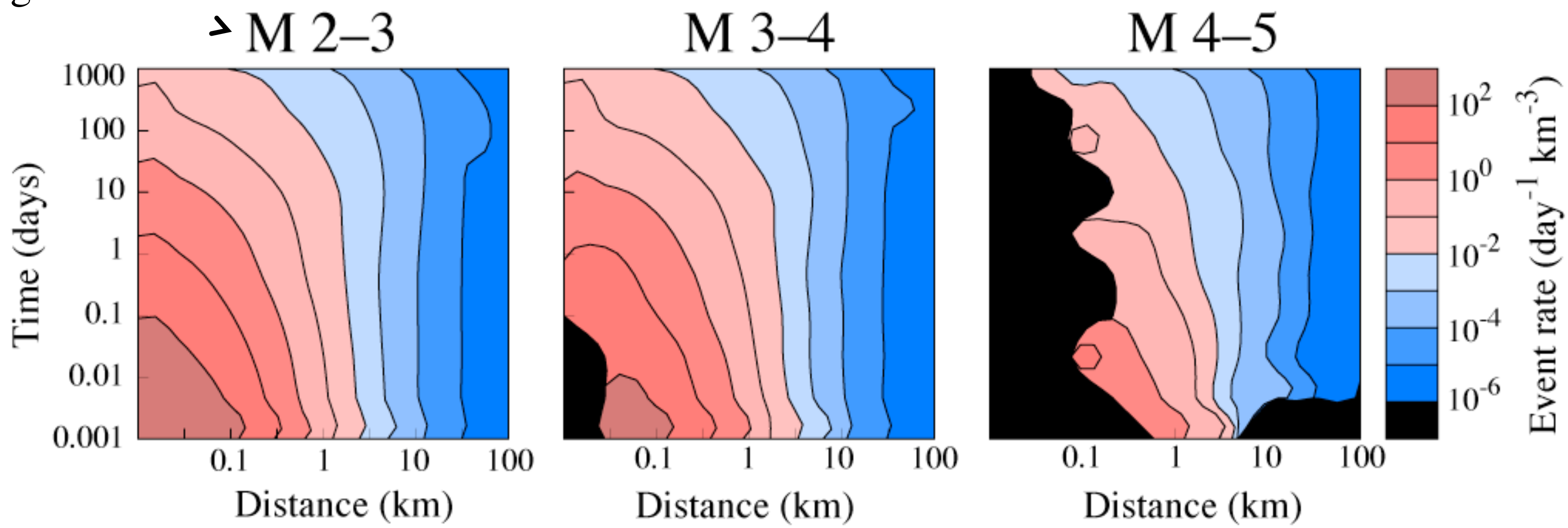


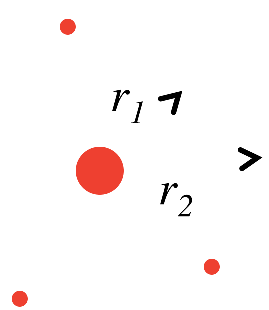
Guoqing Lin

- 1981–2005, relocated using waveform cross-correlation to precision of tens of meters
- Windowed to inside network only, M ≥ 1.5, 173,058 quakes
- Target events excluded for several months following M ≥ 6 mainshocks, and for 3 days following M ≥ 4 quakes

Space/time behavior of precursory seismicity

target event size





precursory event rate

total number of precursory events

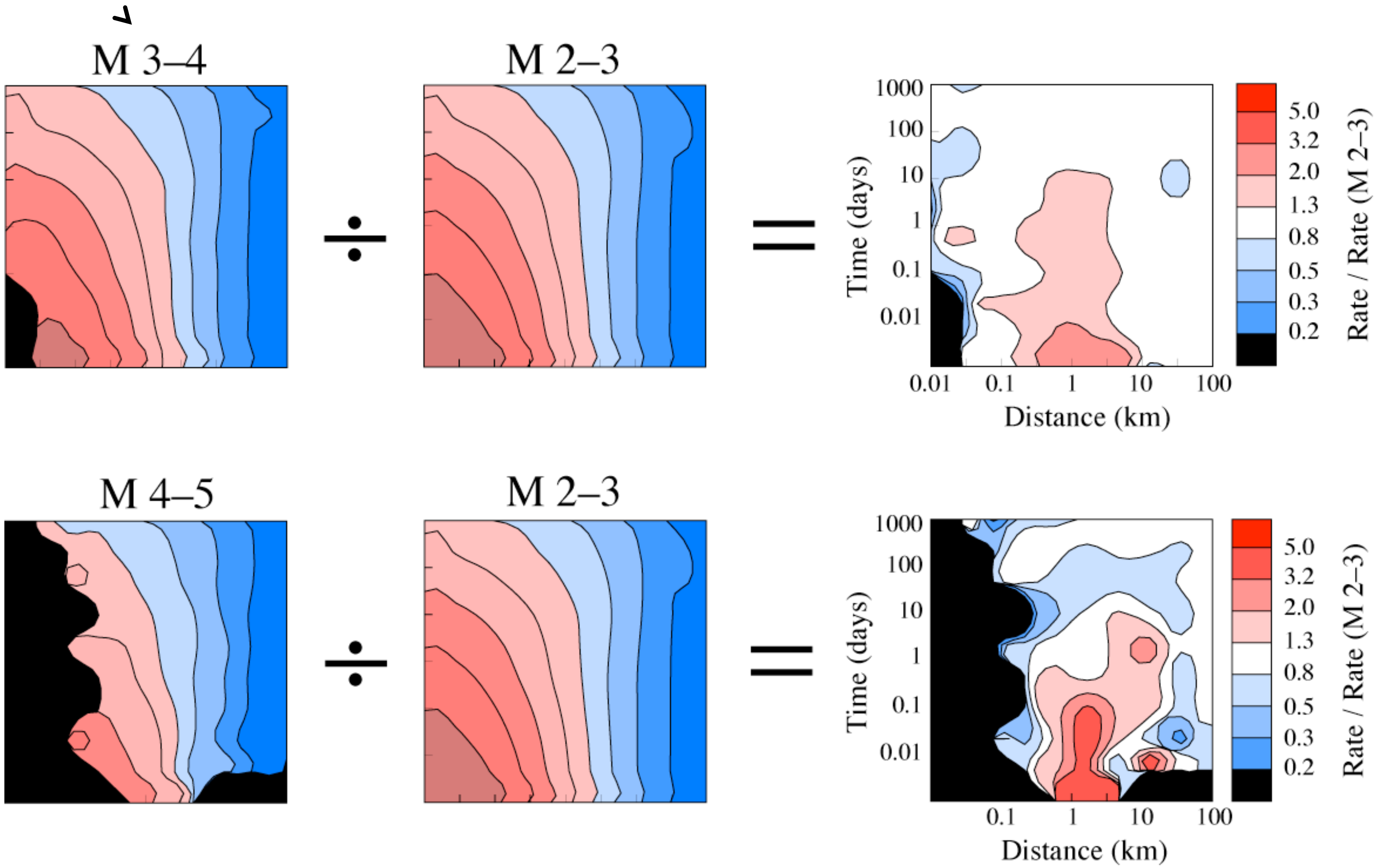
$$D = \frac{n}{N(t_2 - t_1)(4/3)\pi(r_2^3 - r_1^3)}$$

dt volume of shell

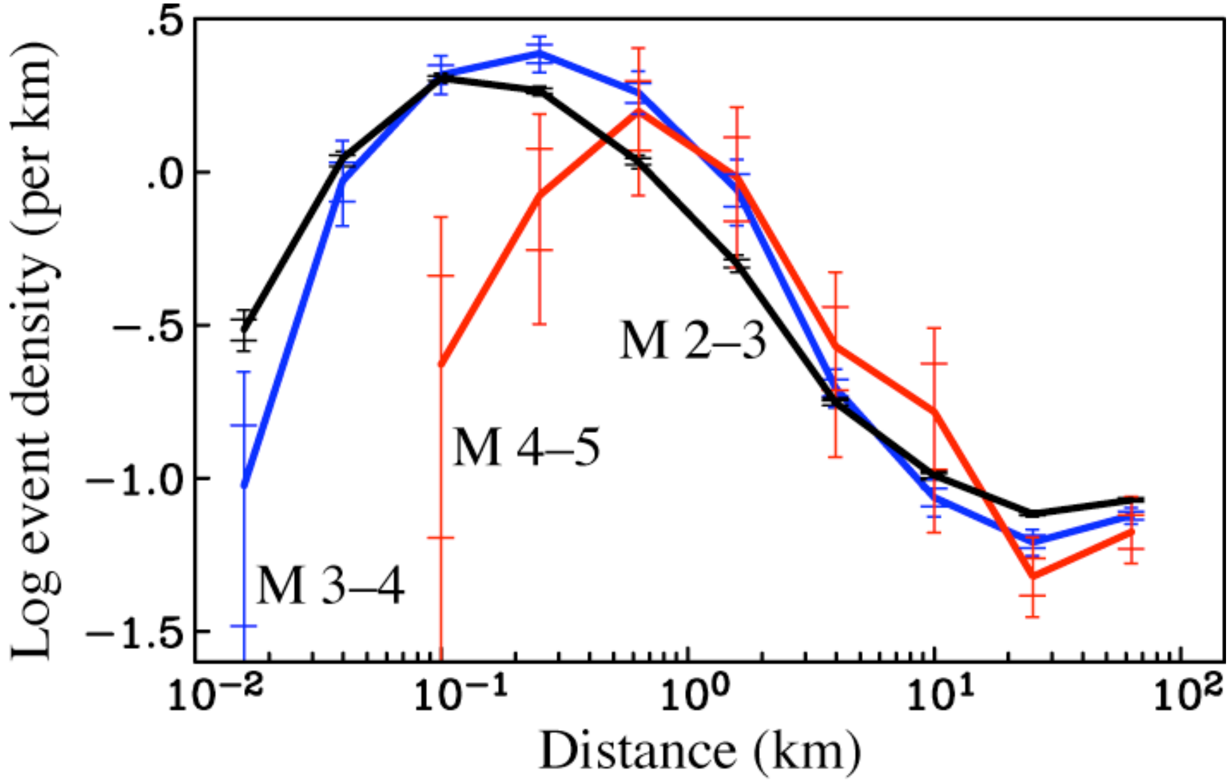
number of target events

Magnitude dependence of precursory seismicity rate

target event size

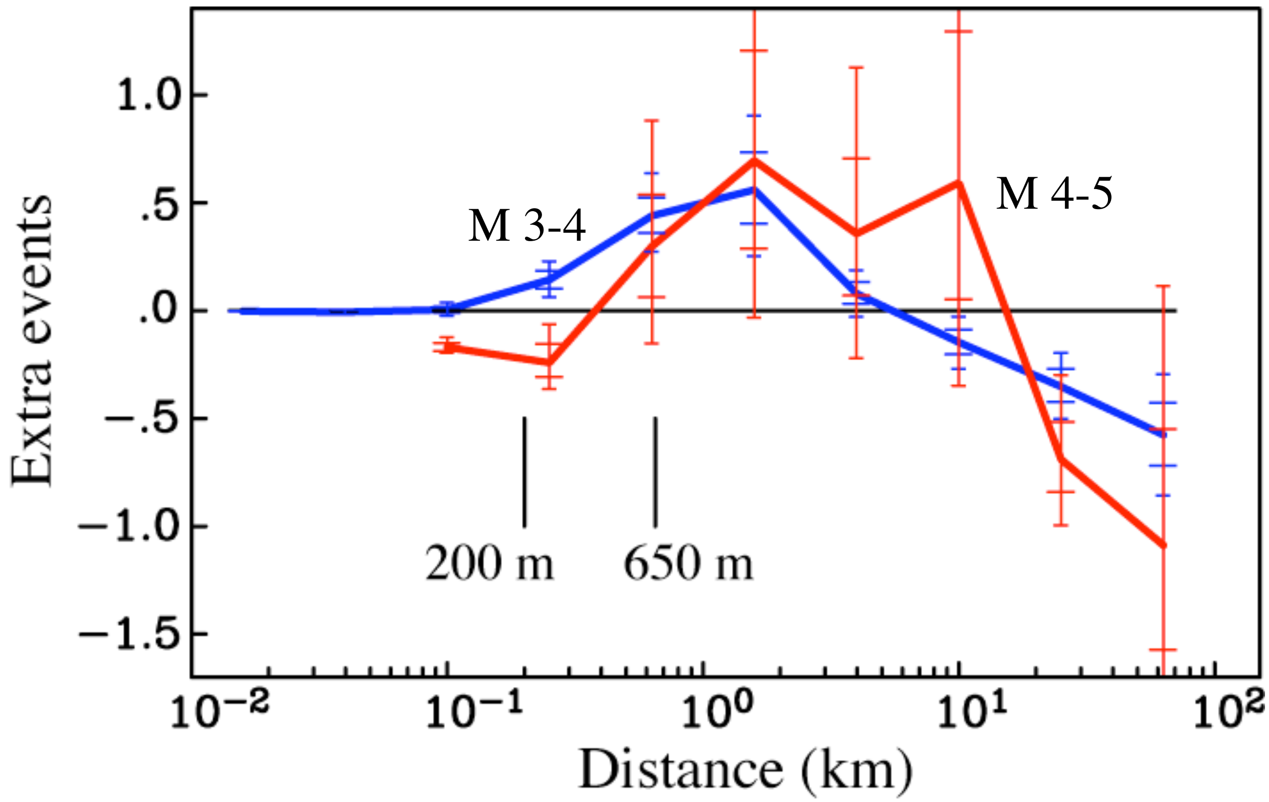


Linear event density in day before target quakes



$$D_{lin} = \frac{n}{N(r_2 - r_1)}$$

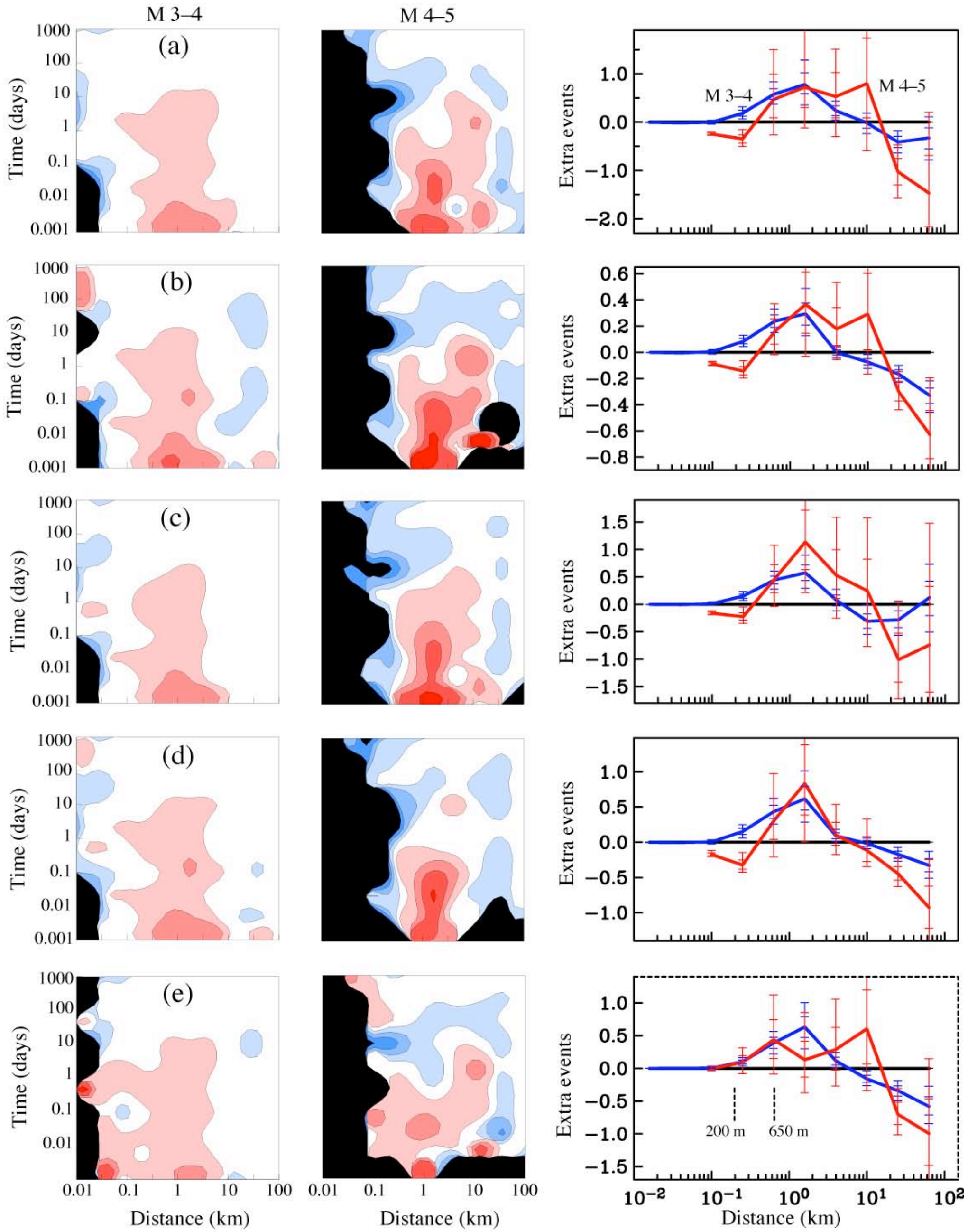
“Extra” precursory events at larger magnitudes



Extra events in each distance bin per target event (compared to M 2-3 results)

> $$E = \frac{n}{N} - \frac{n_{(M2-3)}}{N_{(M2-3)}}$$

How robust is this result?



M ≥ 1 catalog

M ≥ 2 catalog

Halved aftershock exclusion period

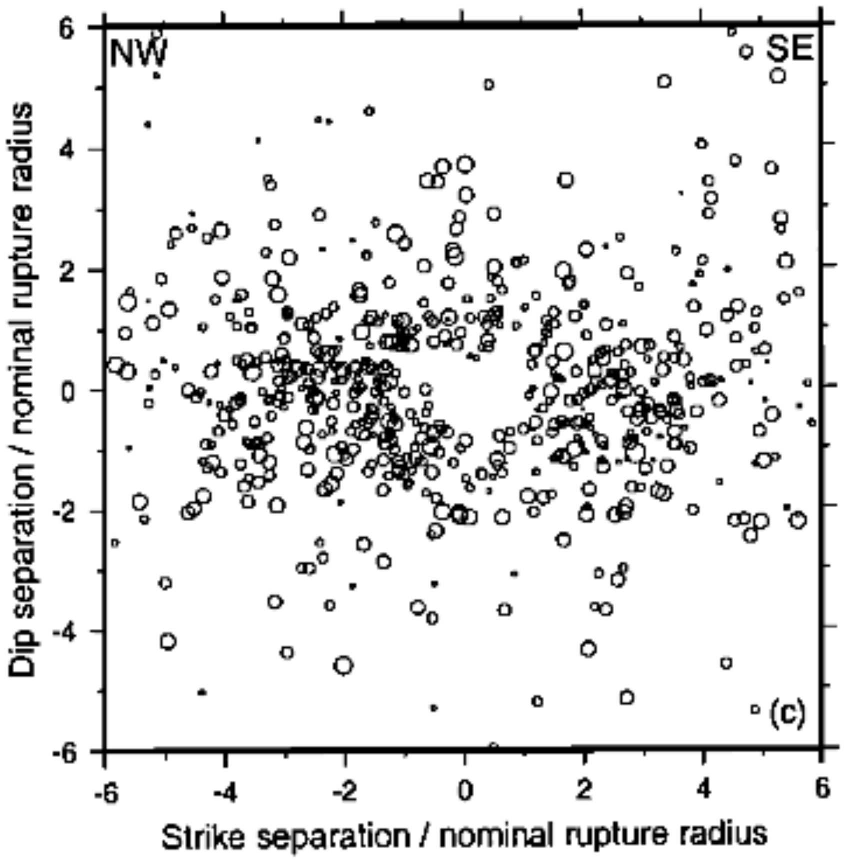
Doubled aftershock exclusion period

Catalog with less accurate locations but more uniformly processed

Precursory Seismicity in Southern California

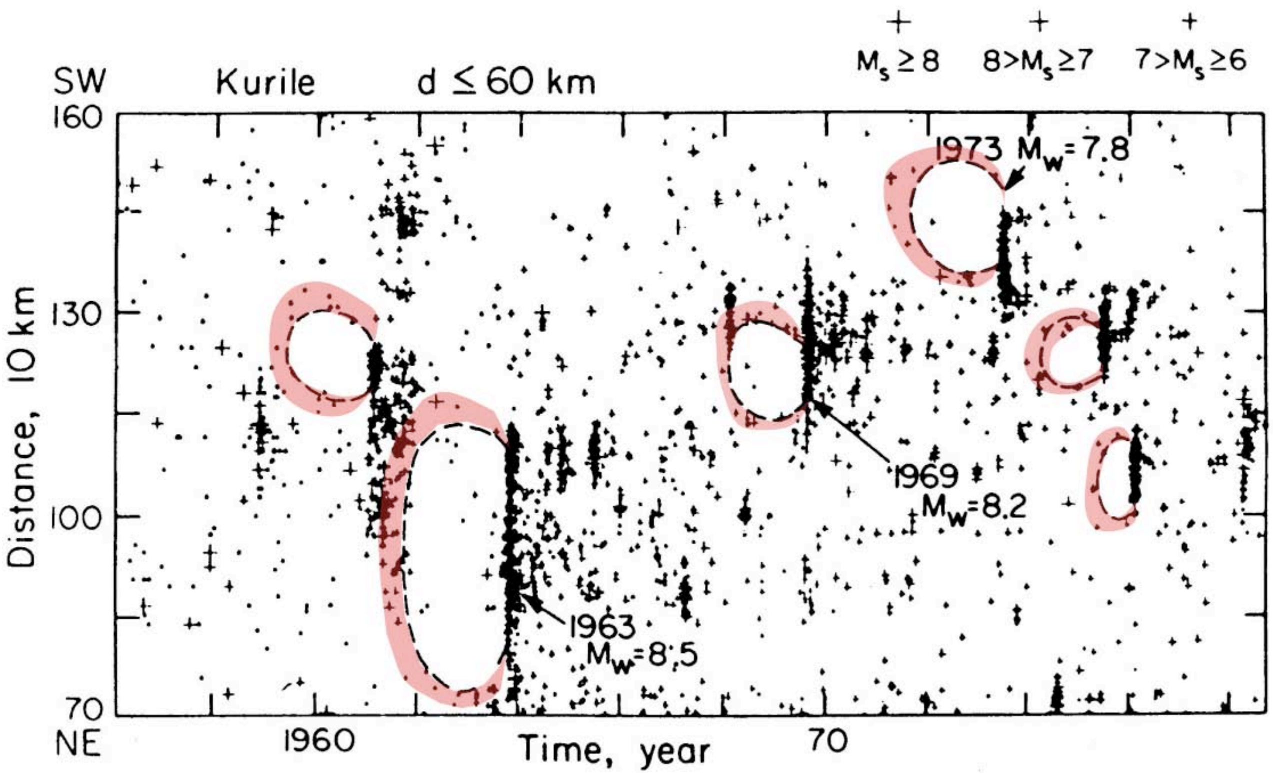
- Enhanced activity in 1-day period preceding M 3-5 quakes compared to M 2-3 quakes at distances of 0.5 to 2 km.
- Anomaly onset roughly agrees with expected source radius of target quakes.
- Reduced activity at shorter distances.
- Not useful for prediction of individual quakes.
- These anomalies are NOT predicted by standard earthquake triggering models.

Aftershock study of Rubin & Gillard (2000)



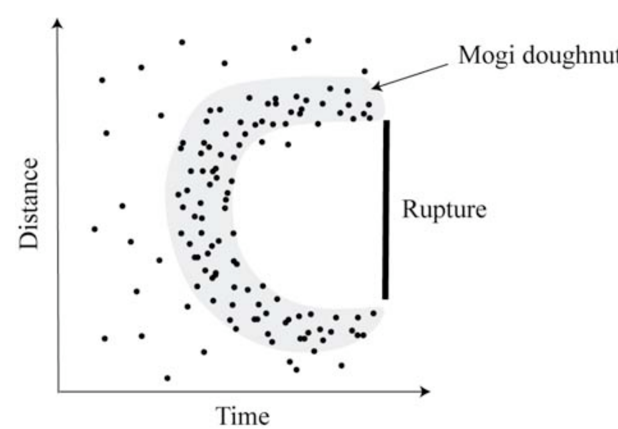
- High-precision relocations of 4300 quakes on central San Andreas Fault
- Plot shows first event following M 1–3.5 mainshocks, scaled by expected source radius of mainshock, assuming 10 MPa stress drop
- “Hole” indicates likely slip plane
- A really nice study!

Mogi doughnuts (*Mogi*, 1969)



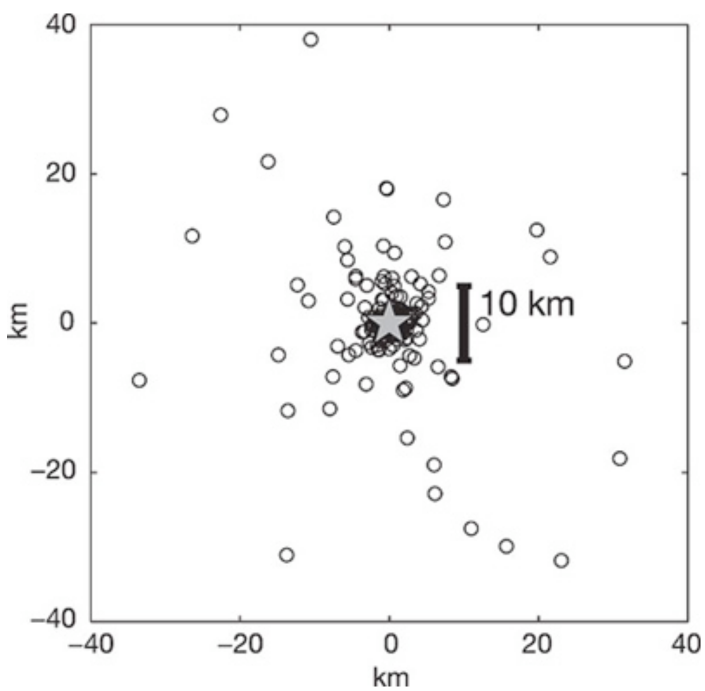
Kanamori (1981)

idealized version

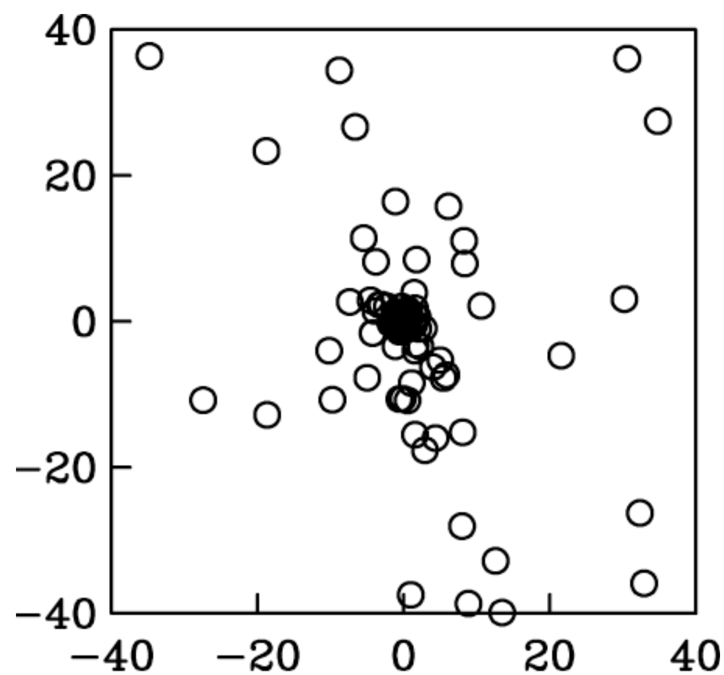


Felzer & Brodsky (2006), revisited

- Picked target events with no larger earthquake within 3 days before and 0.5 day afterward
- Plotted events within 30 minutes after M 3–4 targets



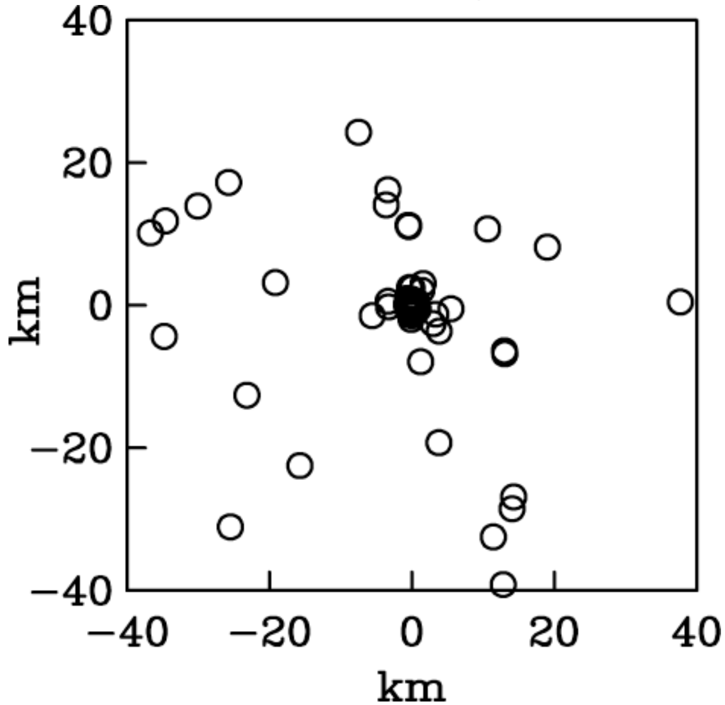
their plot (SHLK catalog)



my plot (LSH catalog)

But similar behavior seen *before* target earthquakes

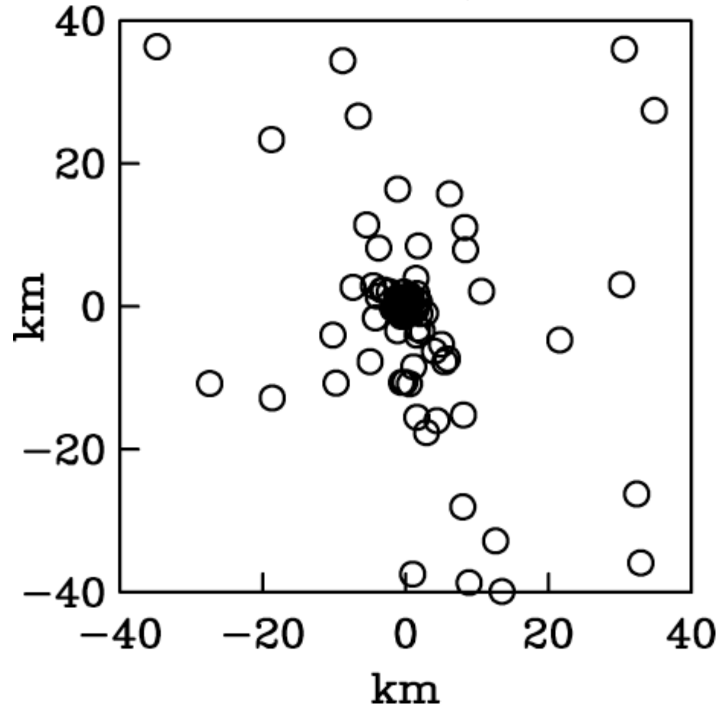
M 3-4 targets



30 minutes before

243 “foreshocks”

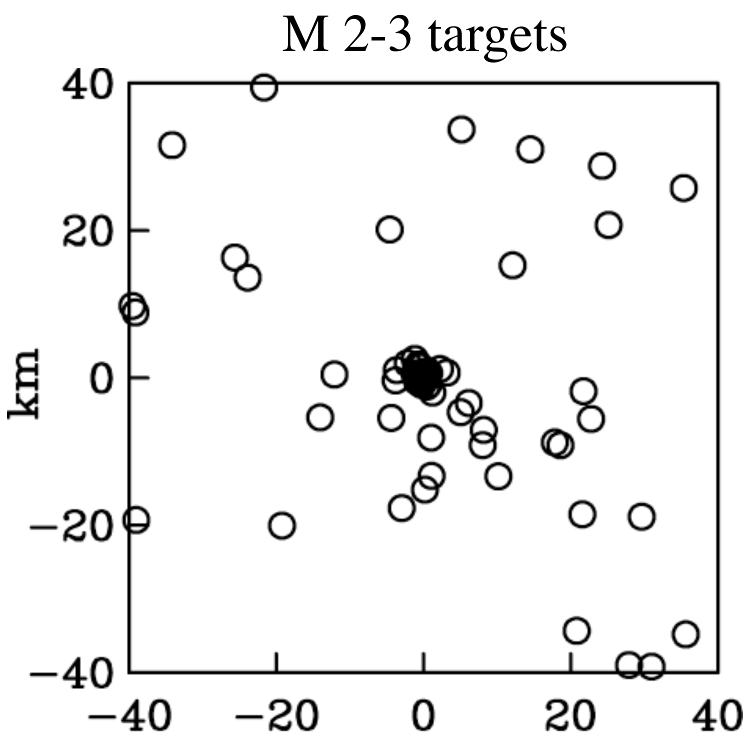
M 3-4 targets



30 minutes after

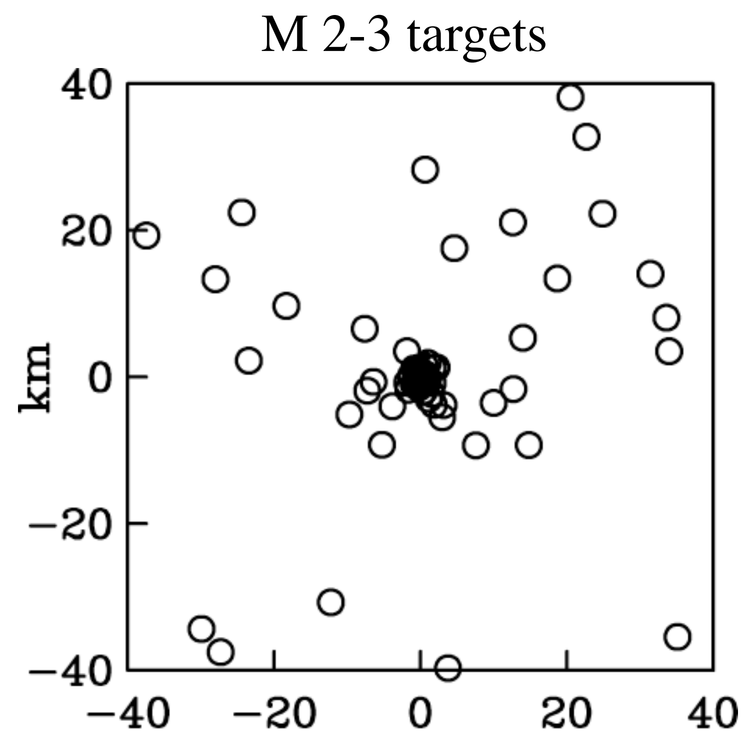
605 “aftershocks”

Behavior for M 2-3 targets is nearly time-symmetric



30 minutes before

322 “foreshocks”



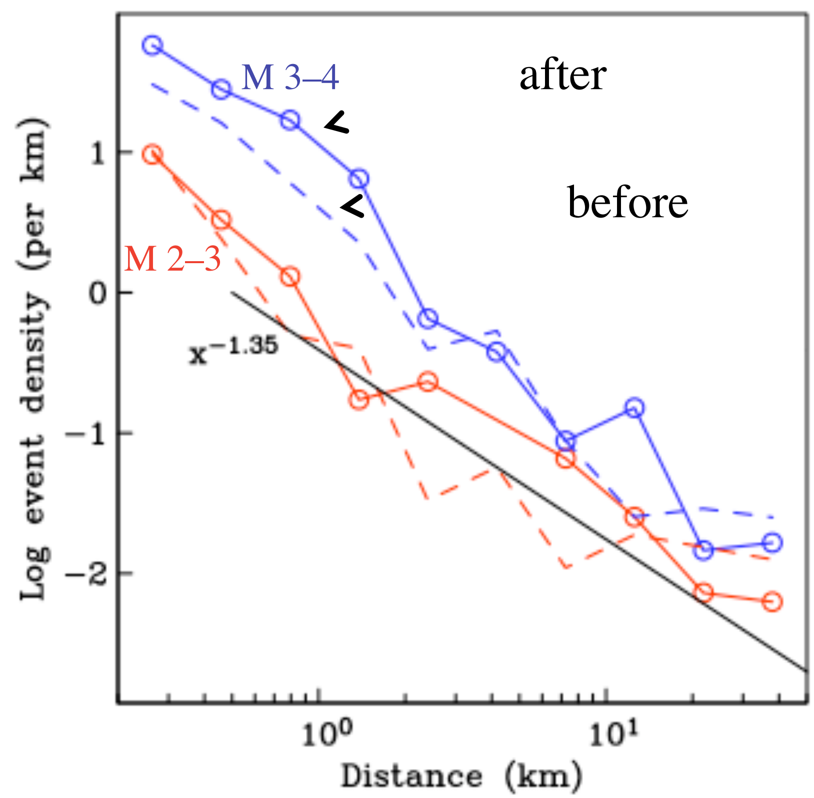
30 minutes after

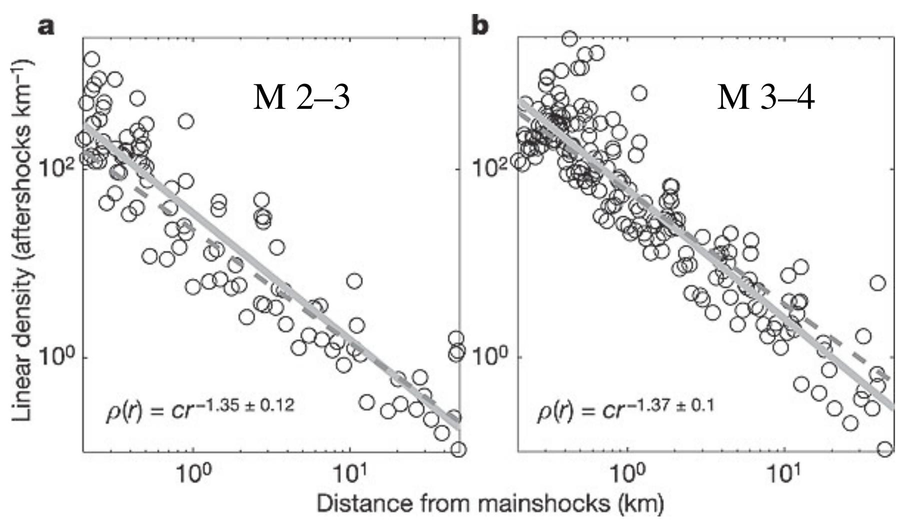
396 “aftershocks”

Felzer & Brodsky (2006), revisited

- Picked target events with no larger earthquake within 3 days before and 0.5 day afterward
- Plotted events within 5 minutes after M 2–3 and M 3–4 targets

LSH catalog results

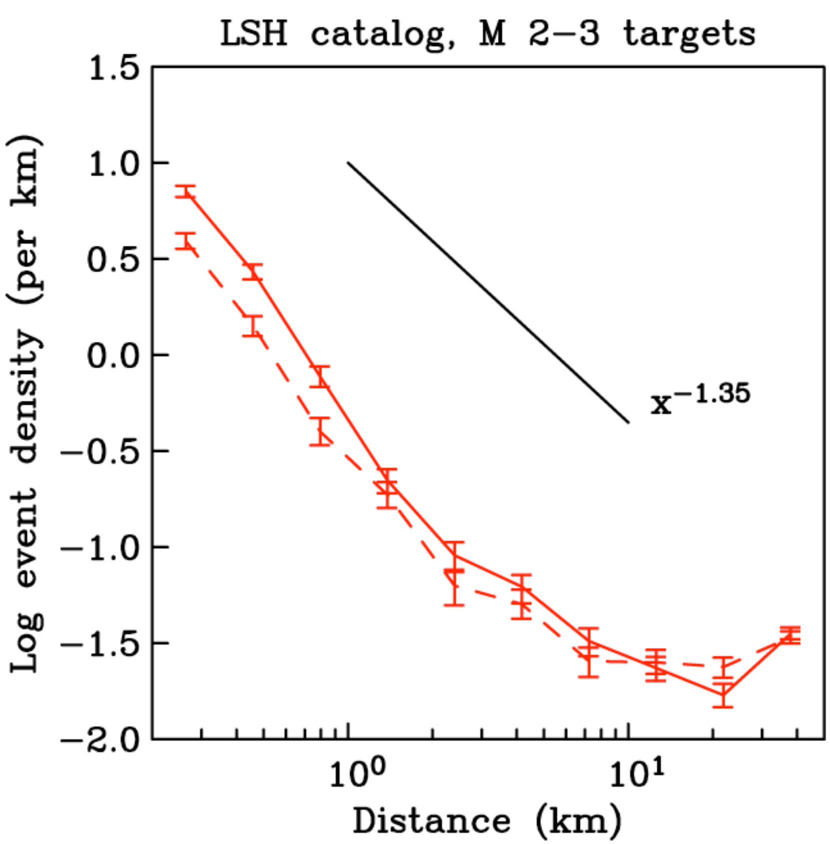


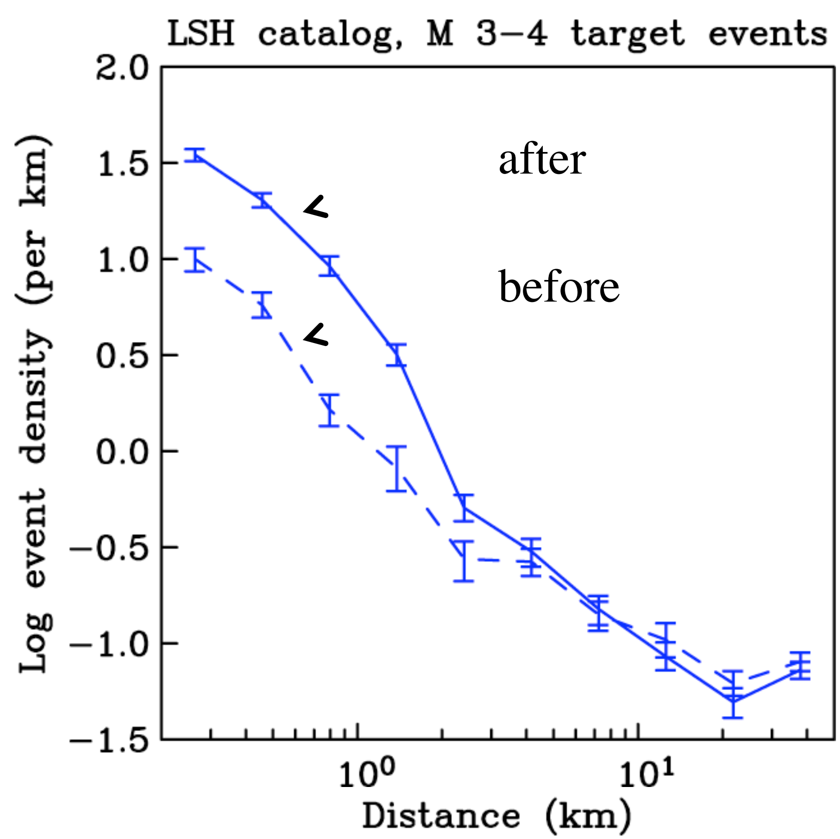


Felzer & Brodksy (2006)

M 2–4 triggering only resolvable to distances of 1 to 3 km

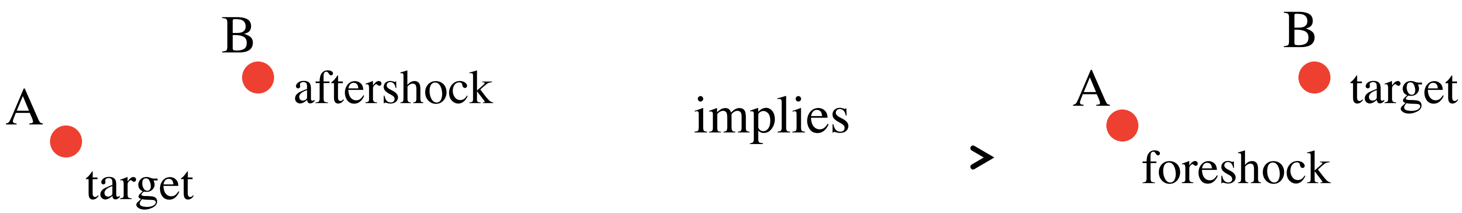
- F&B exclusion criteria
- M ≥ 1.5
- ± 1 hour from target event times





What causes precursory clustering?

Simple AB/BA symmetry argument?



No! Plots are only of events *smaller* than targets.

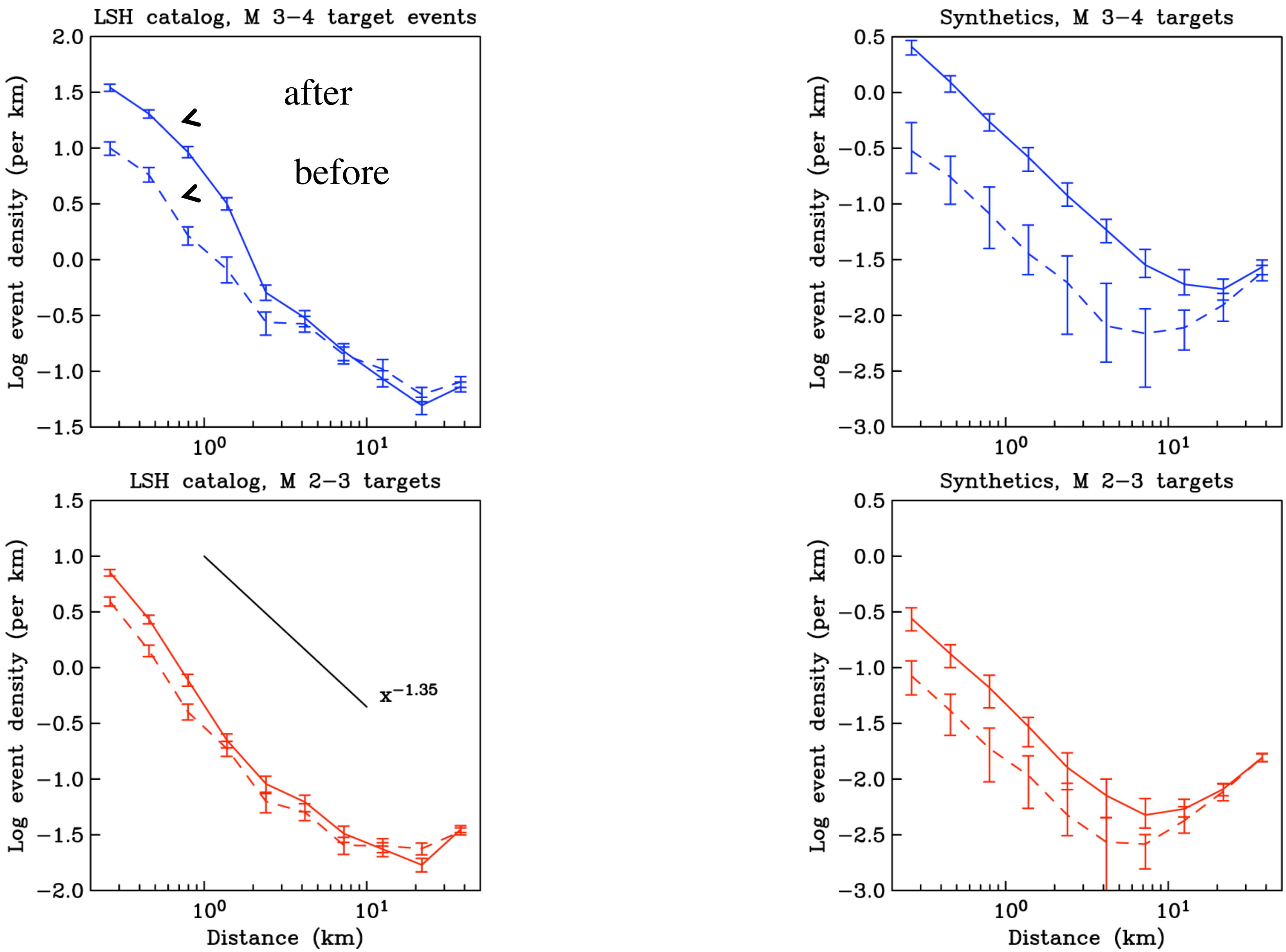
What causes precursory clustering?

Expected behavior from foreshock triggering?
(sometimes mainshocks are really big aftershocks)

To test this, I performed 100 simulations of S. Calif. seismicity using *Aftsimulator.m* program (Karen Felzer) with $\alpha = 1$, $p = 1.34$, $q = 3.37$, G-R relation with $b = 1$
$\lambda_0(\mathbf{x})$ = background rate for S. Calif. (Andy Michael)

$$\lambda(\mathbf{x}, t) = \lambda_0 + \sum_i \kappa 10^{\alpha(m_i - m_0)} (t_i + c)^{-p} r_i^{-q}$$

Data vs ETAS synthetics (M ≥ 1.5)



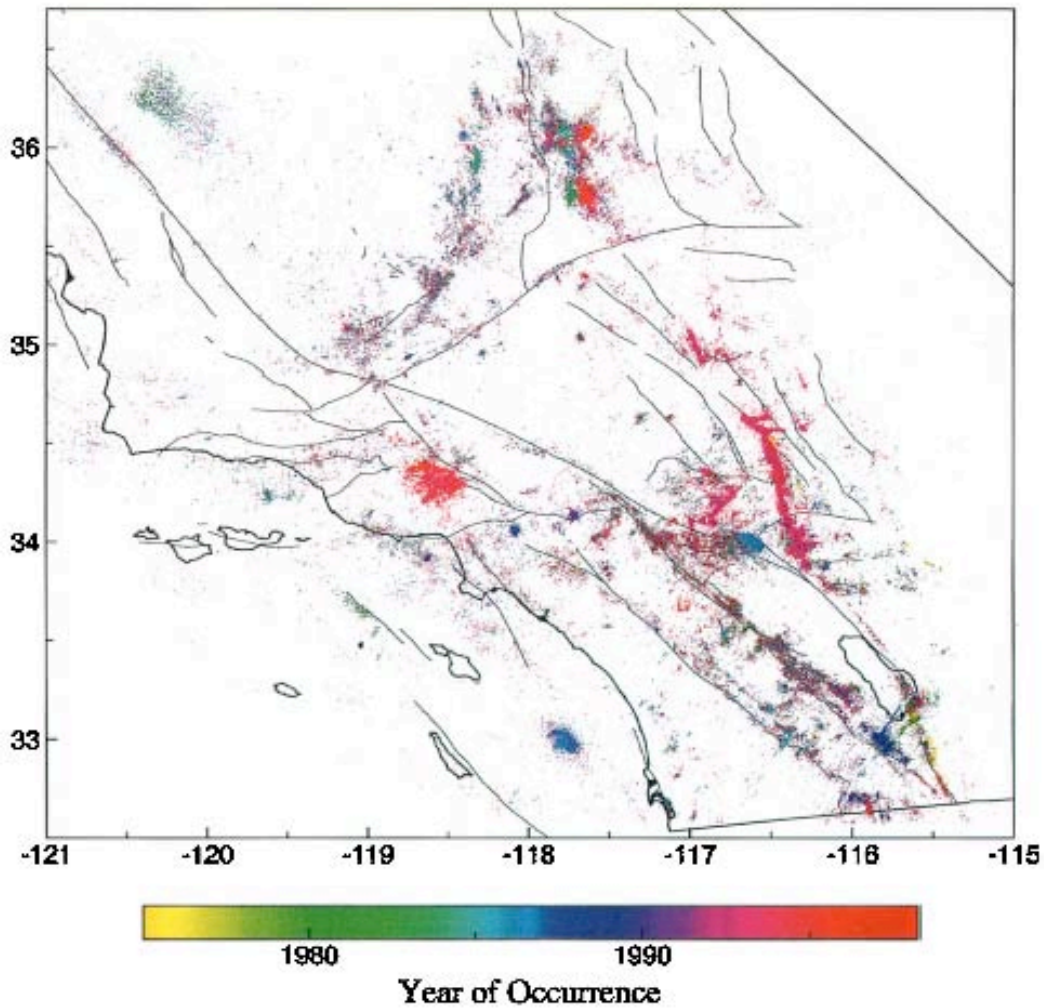
What causes precursory clustering?

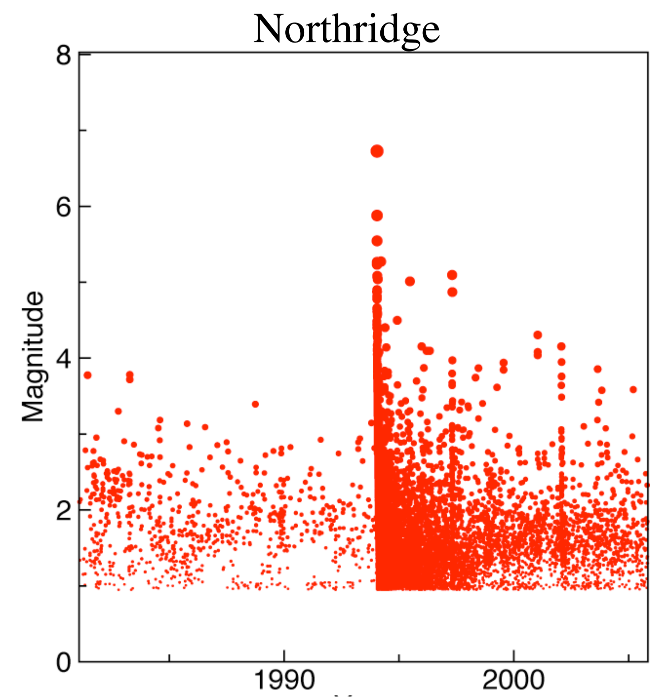
- Simulations suggest that the bulk of time-symmetric clustering for M 1.5–4 earthquakes in southern California is *not* caused by ETAS-like triggering, but by some other process.

- More simulations are needed to test this conclusion, but it's hard to see how runs that satisfy Bath's Law will produce time-symmetric behavior.

- Swarms provide additional evidence for an underlying physical driving mechanism for clustering.

- Important issue for earthquake prediction (ETAS models are totally random and limit how good predictions can be).





Circles show M ≥ 4