A Common Origin for Aftershocks, Foreshocks, and Multiplets

Karen R. Felzer[1], Rachel E. Abercrombie[2], Göran Ekström[1]

[1]Harvard University, [2]Boston University

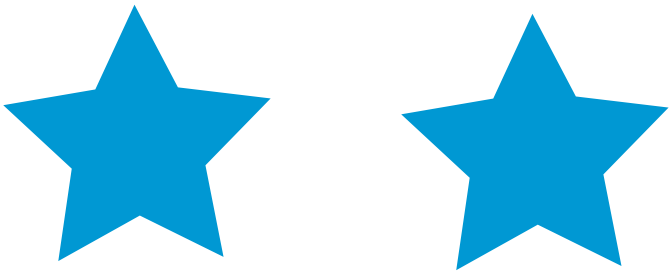
Definitions of clustered seismicity

Aftershock Sequence

Large initial earthquake

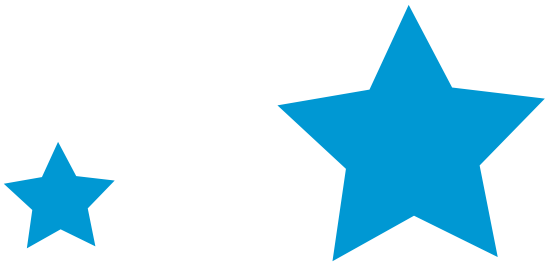
smaller subsequent earthquakes

Doublets or Multiplets



Earthquake(s) are similar in size.
Max $\Delta M = 0.4$, max $\Delta t = 2$ days.
(*Lay and Kanamori*, 1980; *Wesnousky* et al., 1986; *Xu and Schwartz*, 1993.)

Foreshock Sequence



small initial earthquake

larger subsequent earthquake

Do these distinctions indicate different physics?

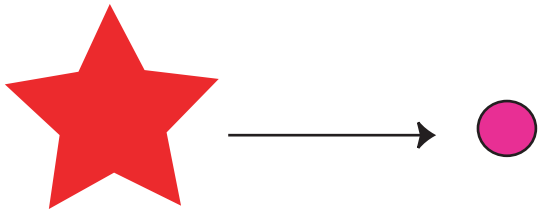
Objectives

Earthquake Statistics

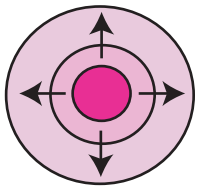
- Test predictions of the single mode triggering model

- Test challenges to the single mode triggering model

Single Mode Triggering Model



One earthquake triggers slip at the hypocenter of *n* future earthquakes, where *n* is proportional to the initial earthquake's area$\propto 10^{M}$



The triggered earthquakes grow to random magnitudes from the Gutenberg-Richter distribution ($N=10^{a-bM}$)

The triggered earthquakes may be smaller, the same size, or larger than the trigger

Single Mode Triggering Predictions

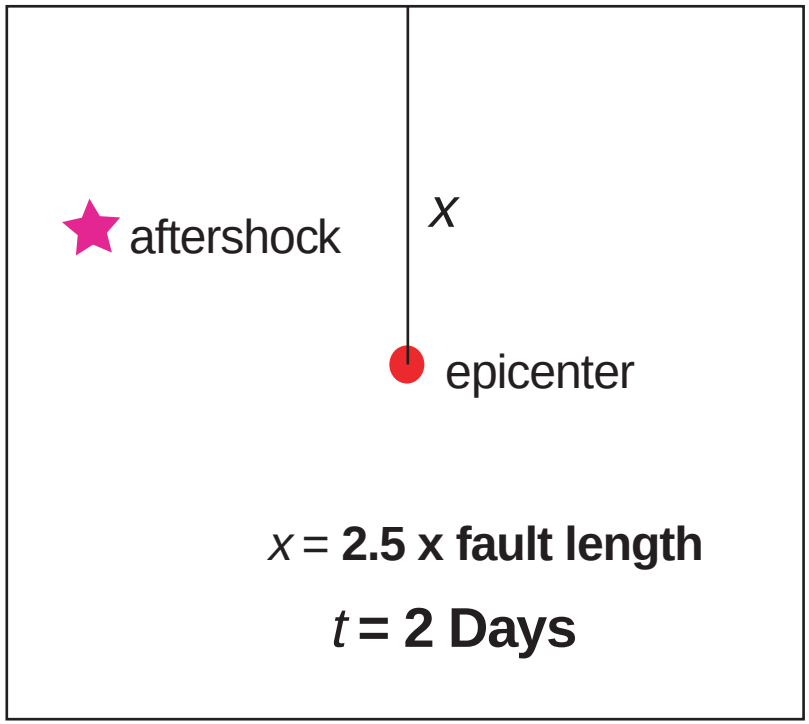
Number of earthquakes triggered by $M_1 \propto 10^{bM_1}$

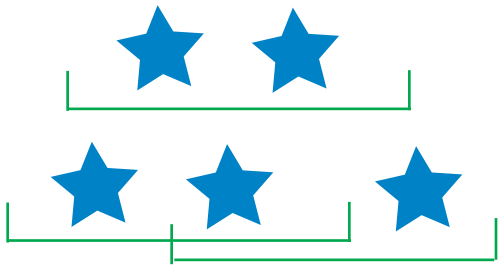
$P(M_2) \propto 10^{-bM_2}$

$P(M_1$ triggering $M_2) \propto 10^{b(M_1-M_2)}$

1. Regional aftershock and doublet rates should vary linearly with each other
2. Regional aftershock and foreshock rates should vary linearly with each other
3. $N(M_2$ aftershocks$) \propto 10^{b(M_1-M_2)}$
4. Larger foreshock → more triggered earthquakes → larger mainshock more probable

Testing the predictions: counting clustered earthquakes





one doublet

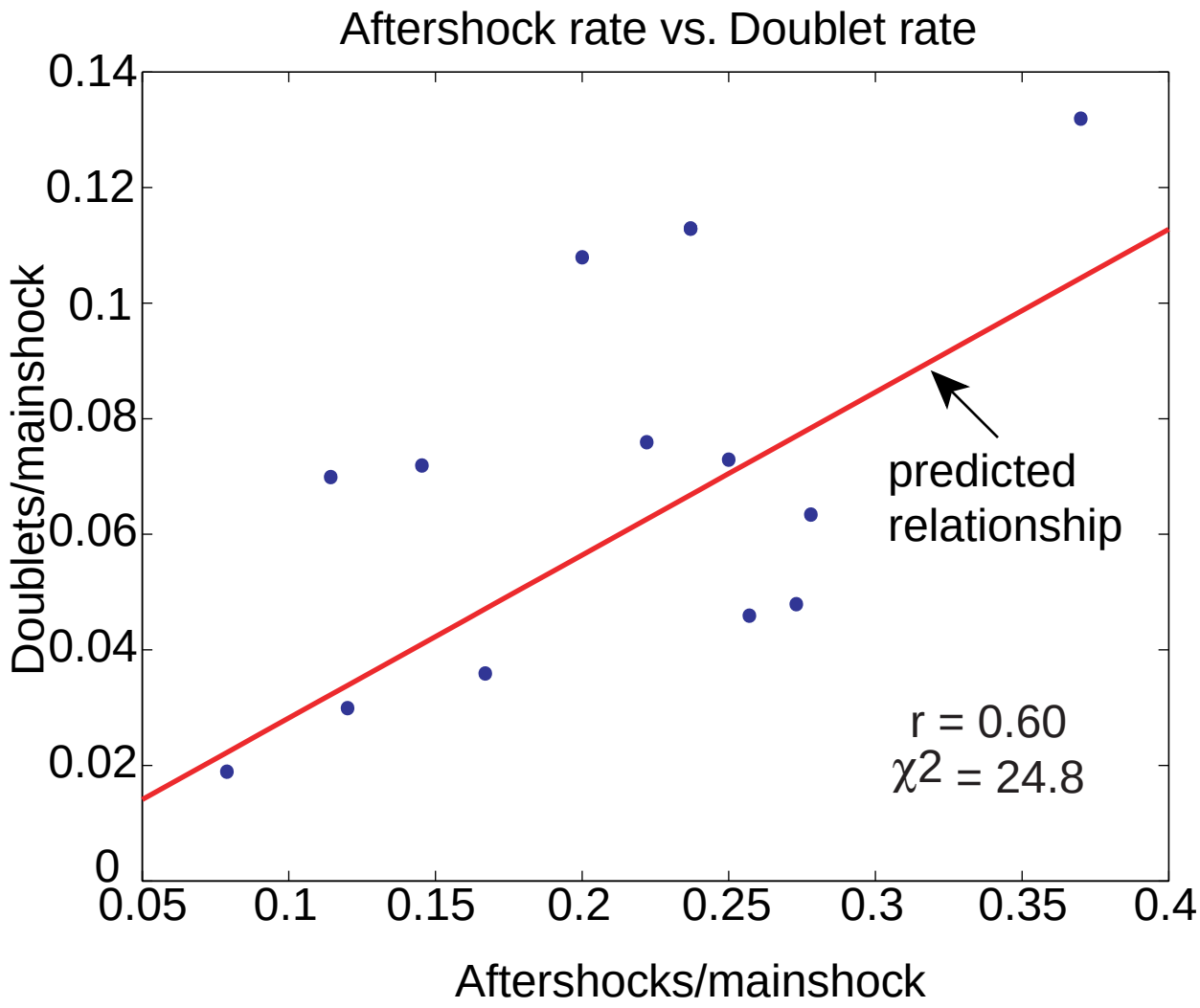
two doublets

Catalog
CMT & NEIC
1975-2002

event type	min M_1	min M_2	$M_1 - M_2$ (ΔM)
doublet	6.4	6.0	$-0.4 \leq \Delta M \leq 0.4$
aftershock	6.6	5.6	$0.4 \leq \Delta M \leq 1.0$
foreshock	5.6	5.7	$\Delta M < 0.0$

Single Mode Triggering Prediction #1

Regional aftershock and doublet rates vary linearly with each other ✔



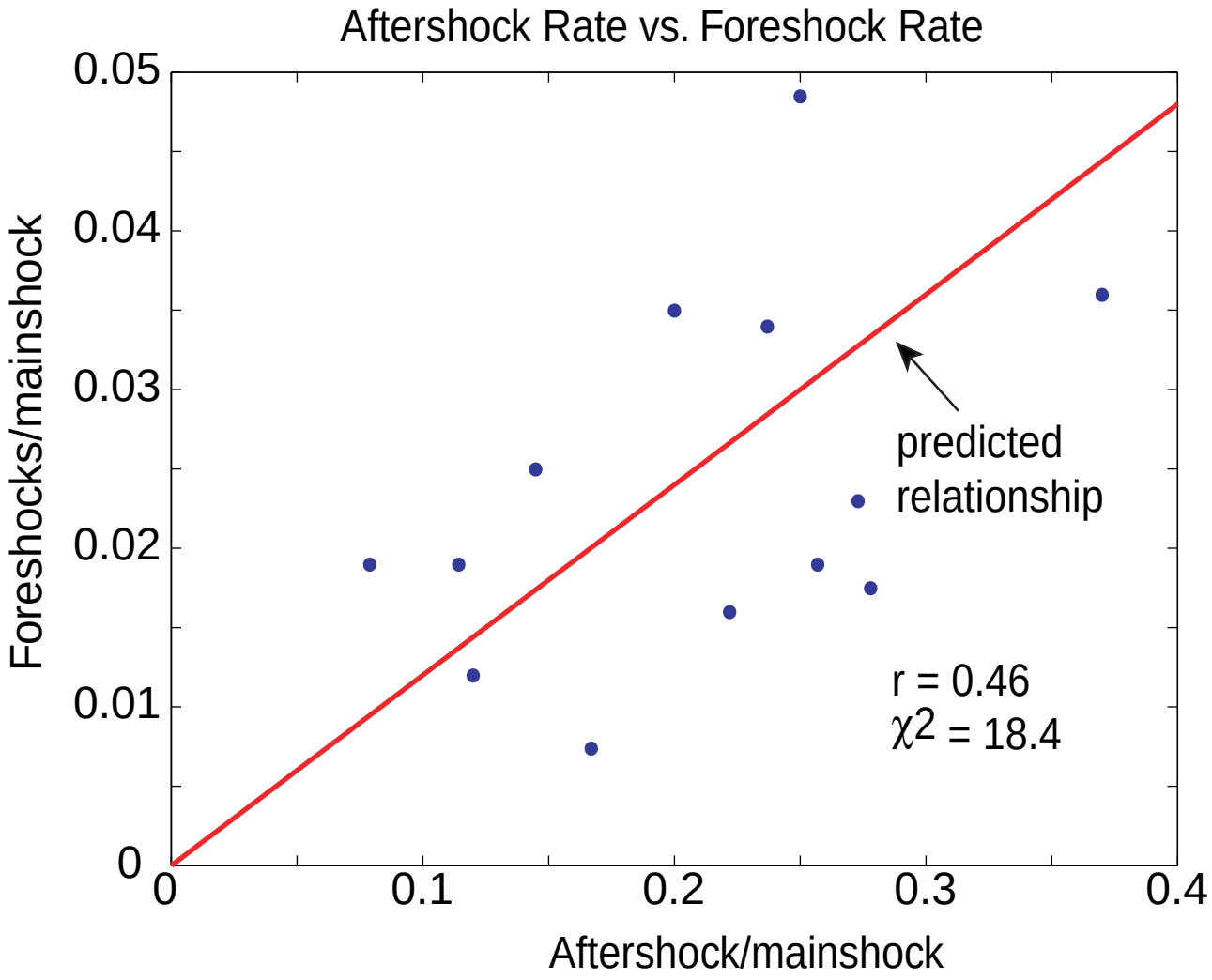
Data points are from:

The Kuriles
The Solomon Islands
New Hebrides
The Phillipines
The Aleutians
New Zealand
Sumatra
West Coast, N. America
Japan
Southern America
Mid-ocean Ridges
Tibet
Italy

t = 2 days x = 2.5 x fault length

Single mode triggering prediction #2

Aftershock and foreshock rates vary with each other ✔



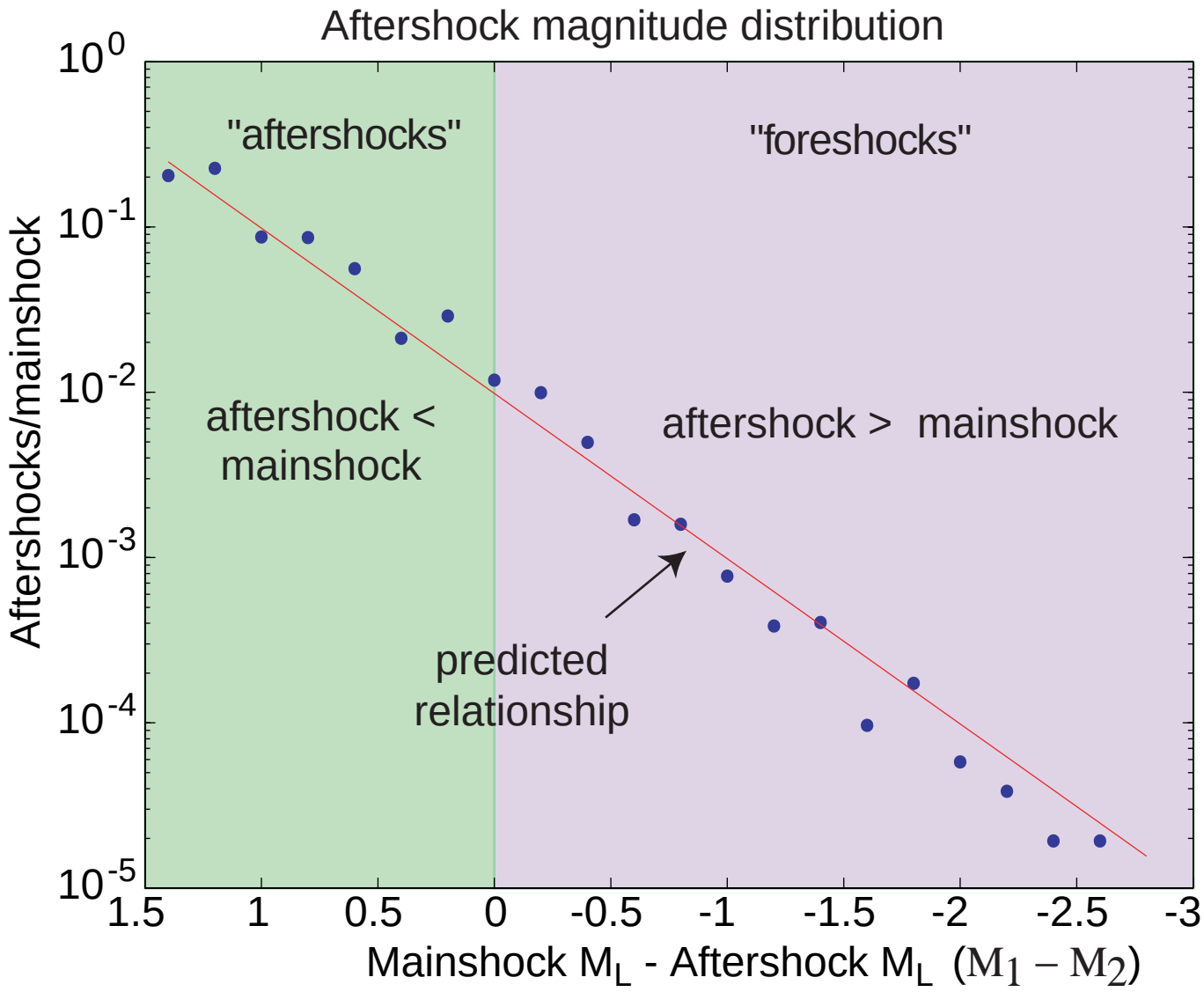
Data points

The Kuriles
The Solomon Islands
New Hebrides
The Phillipines
The Aleutians
New Zealand
Sumatra
West Coast, N. America
Japan
Southern America
Mid-ocean Ridges
Tibet
Italy

t = 2 days x = 2.5 x fault length

Single mode triggering prediction #3

$N(M_2 \text{ aftershocks}) \propto 10^{b(M_1 - M_2)}$ ✔

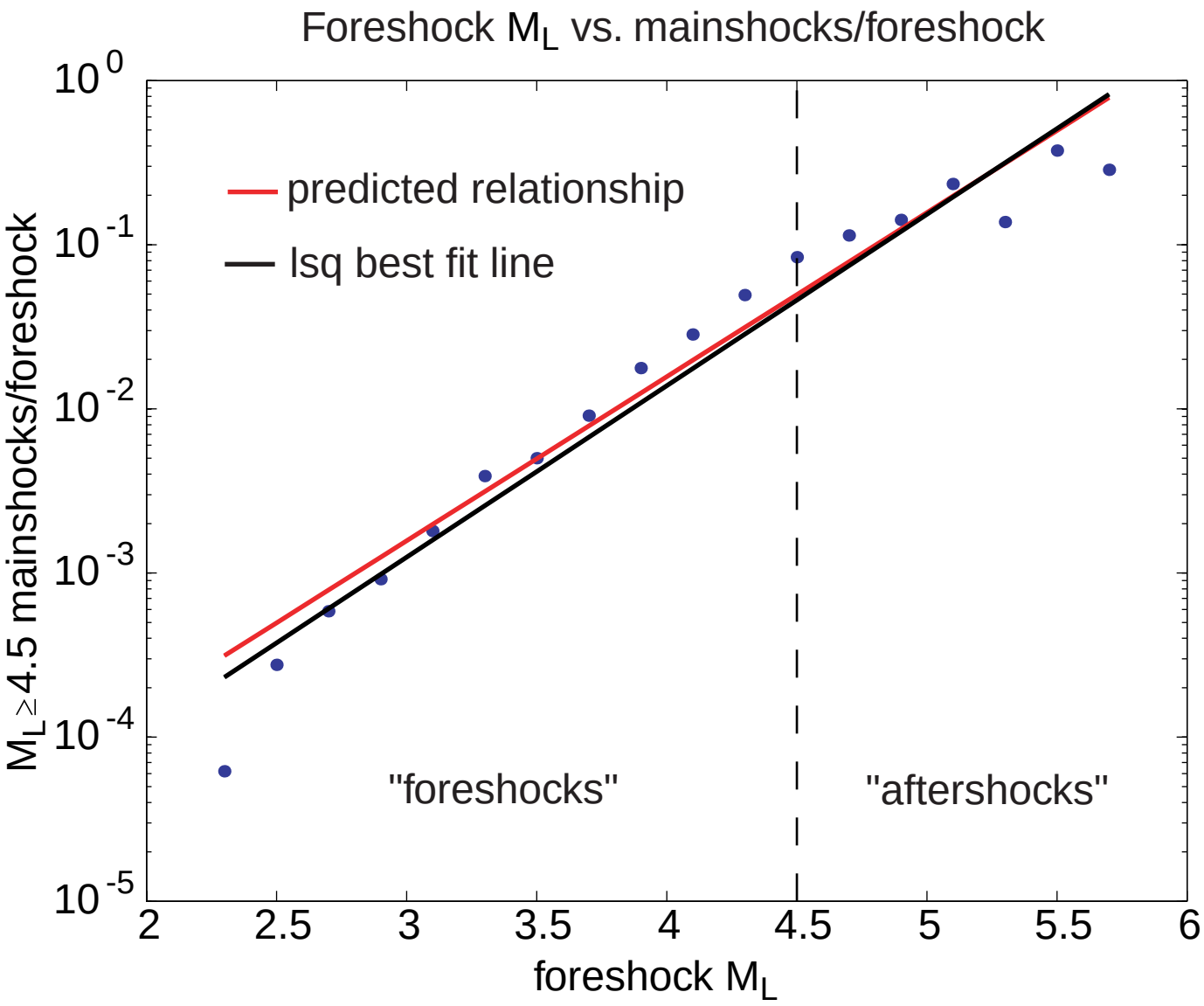


California earthquakes, 1975-2001, M≥2.2 (101,680 eqs)

t = 2 days *x* = 2 x fault length

Single mode triggering prediction #4

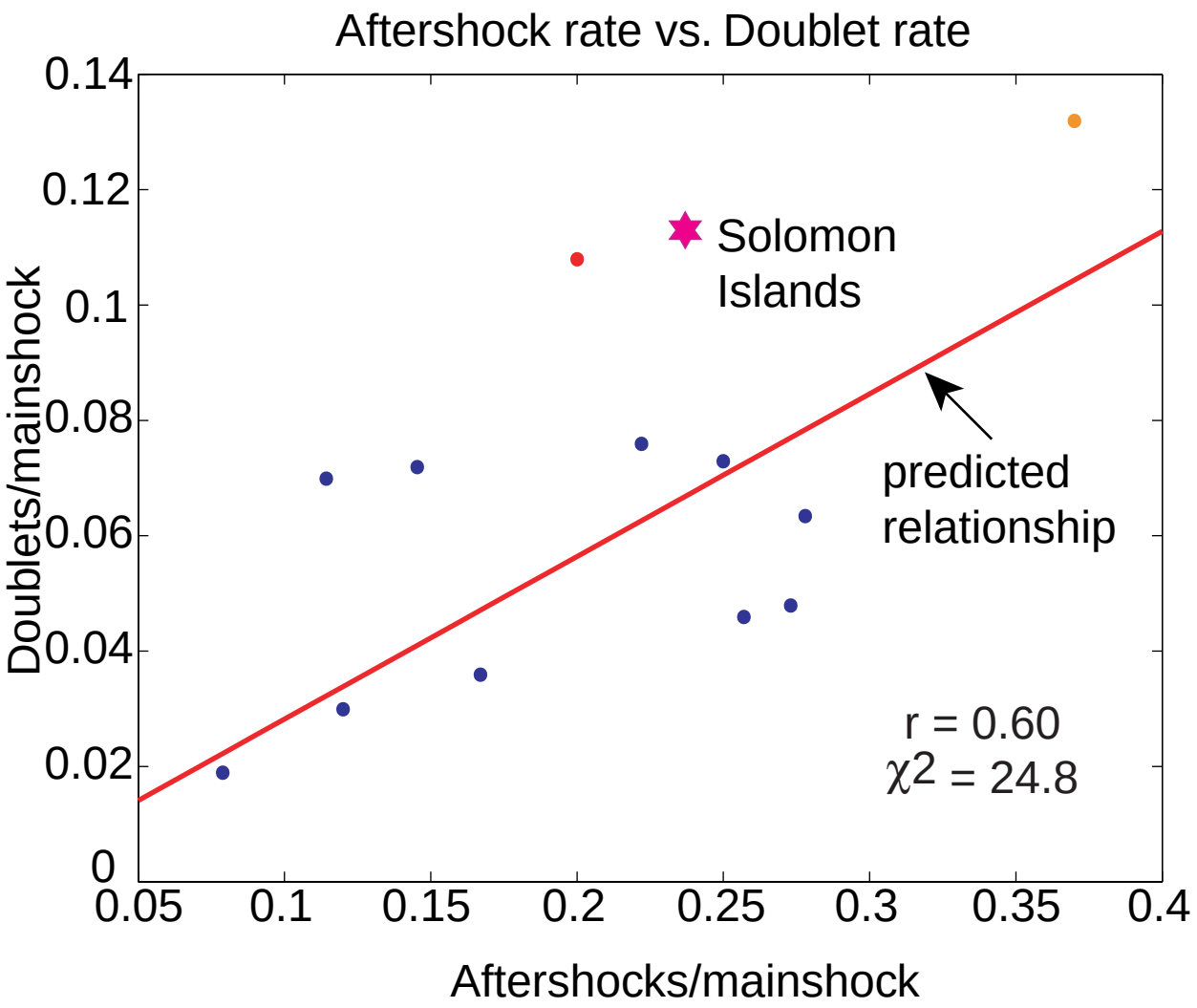
Larger individual foreshocks are more likely to trigger a large mainshock ✔



t = 2 days *x* = 2 x fault length

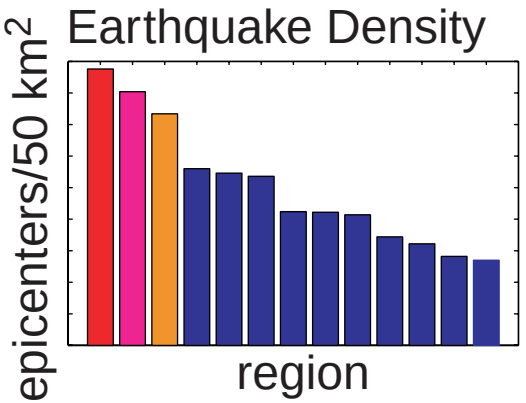
Model Challenge #1

The Solomon Islands have too many doublets



Data points are from:

The Kuriles
The Solomon Islands
New Hebrides
The Phillipines
The Aleutians
New Zealand
Sumatra
West Coast, N. America
Japan
Southern America
Mid-ocean Ridges
Tibet
Italy



Test: Does the doublet rate in the Solomon Islands disprove Single Mode Triggering?

10,000 Monte Carlo Trials

Input

- Number of mainshocks
- Aftershock rate
- Earthquake magnitude distribution

→ single mode triggering model →

Output

- Number of doublets randomly produced

doublet magnitude	no. observed in Solomons	% time expected from random fluctuation
$M \geq 6$	6	38%
$M \geq 7$	4	18%

Observed doublet rates in the Solomons are consistent with single mode triggering

Model Challenge #2

Triggering cannot work small → large

Implications of Challenge #2

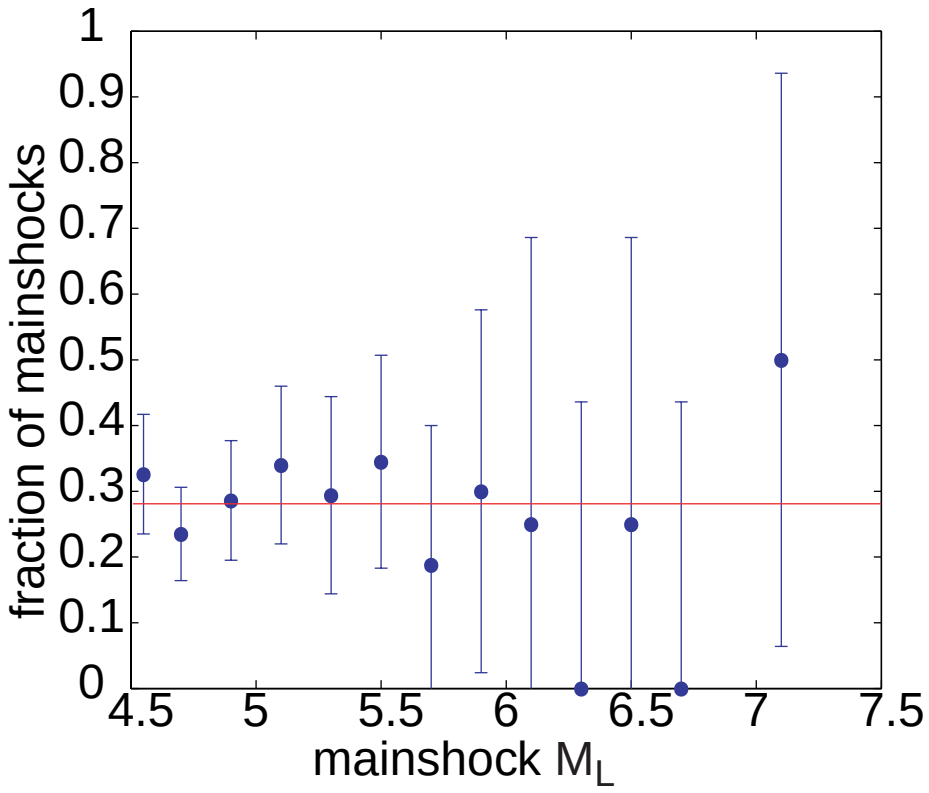
Foreshocks occur because of stressing by the nucleation phase of the mainshock

Predictions of Challenge #2

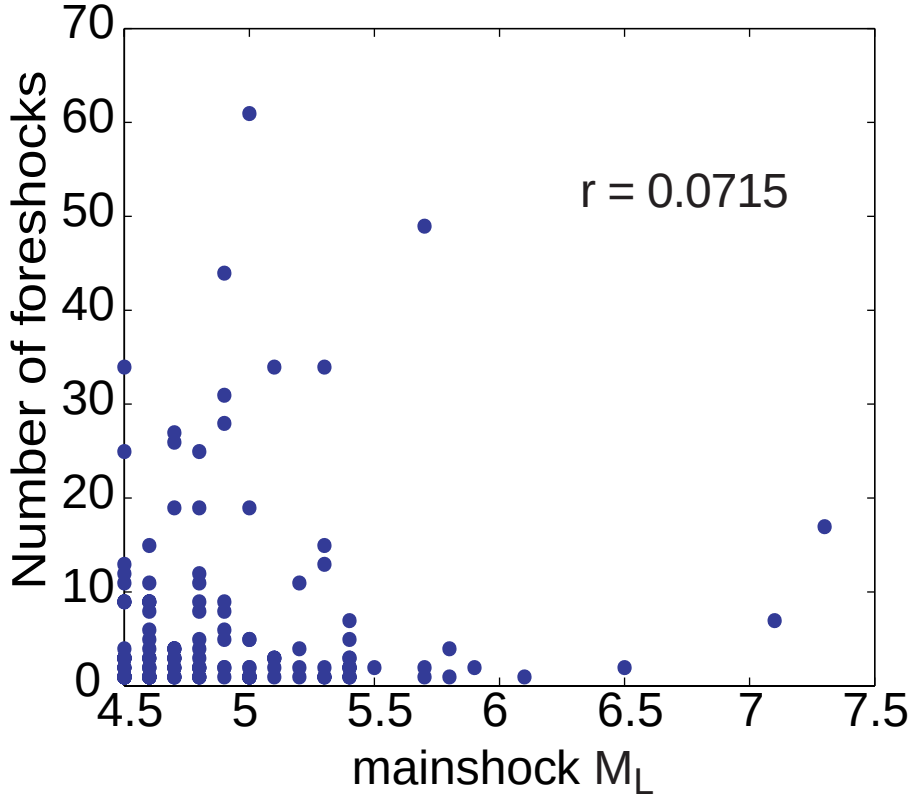
- Nucleation phase size should scale with mainshock magnitude
- Mainshock magnitude should influence foreshock occurrence

Test: Does mainshock size influence foreshocks?

Fraction of California mainshocks with largest foreshock $2.2 \leq M_L \leq 4.5$



Mainshock M_L vs. number of foreshocks $2.2 \leq M_L \leq 4.5$



→ There is no statistical correlation found between mainshock size and foreshock magnitude or number

Conclusions

- Aftershock, doublet, and foreshock rates vary linearly with each other
- The magnitudes of triggered earthquakes may be reproduced by chosing random values from the Gutenberg-Richter distribution
- Foreshock size influences mainshock occurrence
- Mainshock size does not influence foreshocks

Aftershocks, foreshocks, and doublets all result from a single physical triggering process