Are Massive Earthquakes Correlated?

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with: Eric Daub, Robert Guyer, Paul Johnson (LANL)

thanks: Charles Ammon (Penn State), Thorne Lay (UCSC),
Terry Wallace (LANL), Joan Gomberg (USGS), Chunquan Wu (LANL)

E.G. Daub, EB, R.A. Guyer, P.A. Johnson, Geophys. Res. Lett. 39, L06308 (2012)
EB, E.G. Daub, P.A. Johnson, Geophys. Res. Lett. **39**, 3021 (2013)
C. Wu, J. Gomberg, EB, P.A. Johnson, Geophys. Res. Lett. **41**, 1499 (2014)

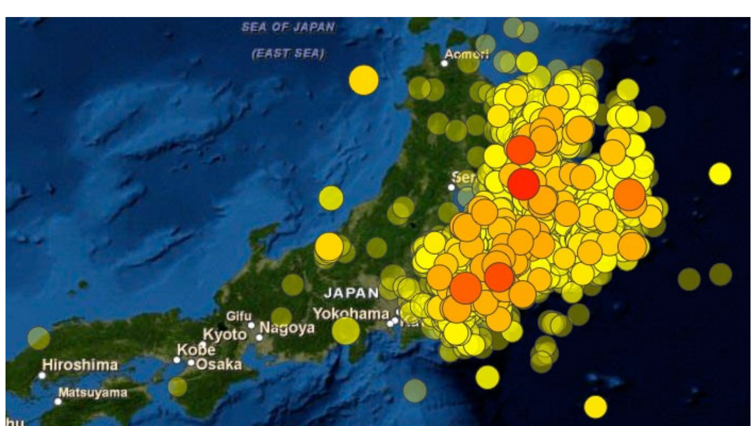
T-4 Blabs, April 20 2015

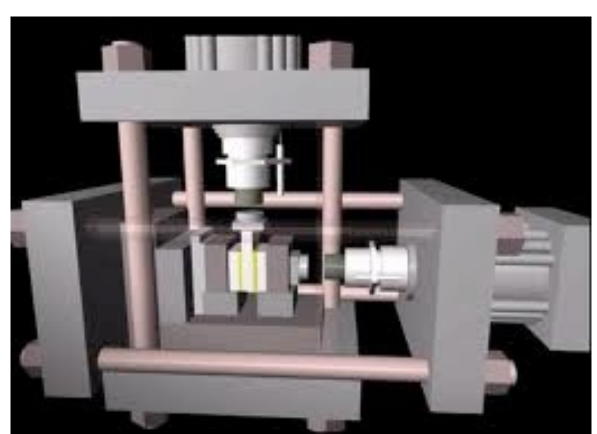
Plan

- Remote triggering of earthquakes
- Statistics of number of events in a time interval
- Statistics of time interval between events

Remote triggering of earthquakes

- We know large earthquakes generate smaller earthquakes locally = aftershocks Gomberg 05
- Do large earthquakes trigger large earthquakes globally?
- Growing evidence for global interactions Lay & Ammon 10
- Earthquake triggering & granular matter project Johnson, PI
  - Experiments in sheared granular matter (PSU,LANL)
  - Simulations of sheared granular matter (ETH, LANL)
  - Field observations, acoustics (Parkfield, CA: USGS, LANL)
  - Statistical analysis (LANL)





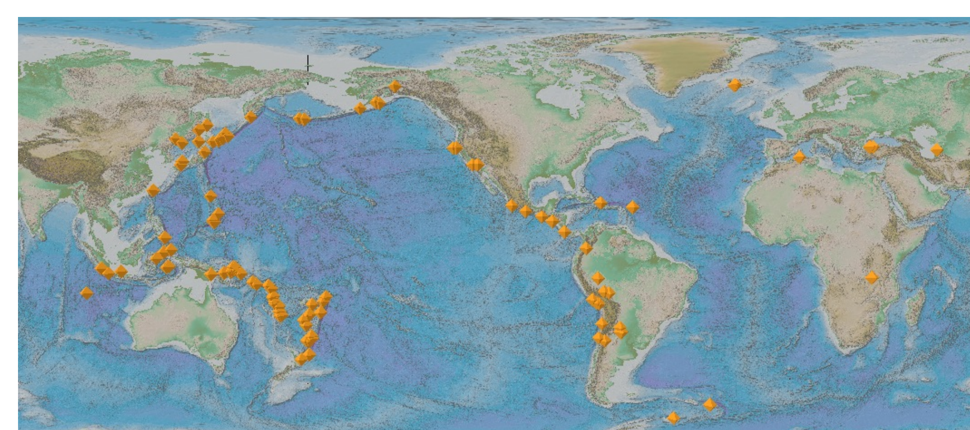
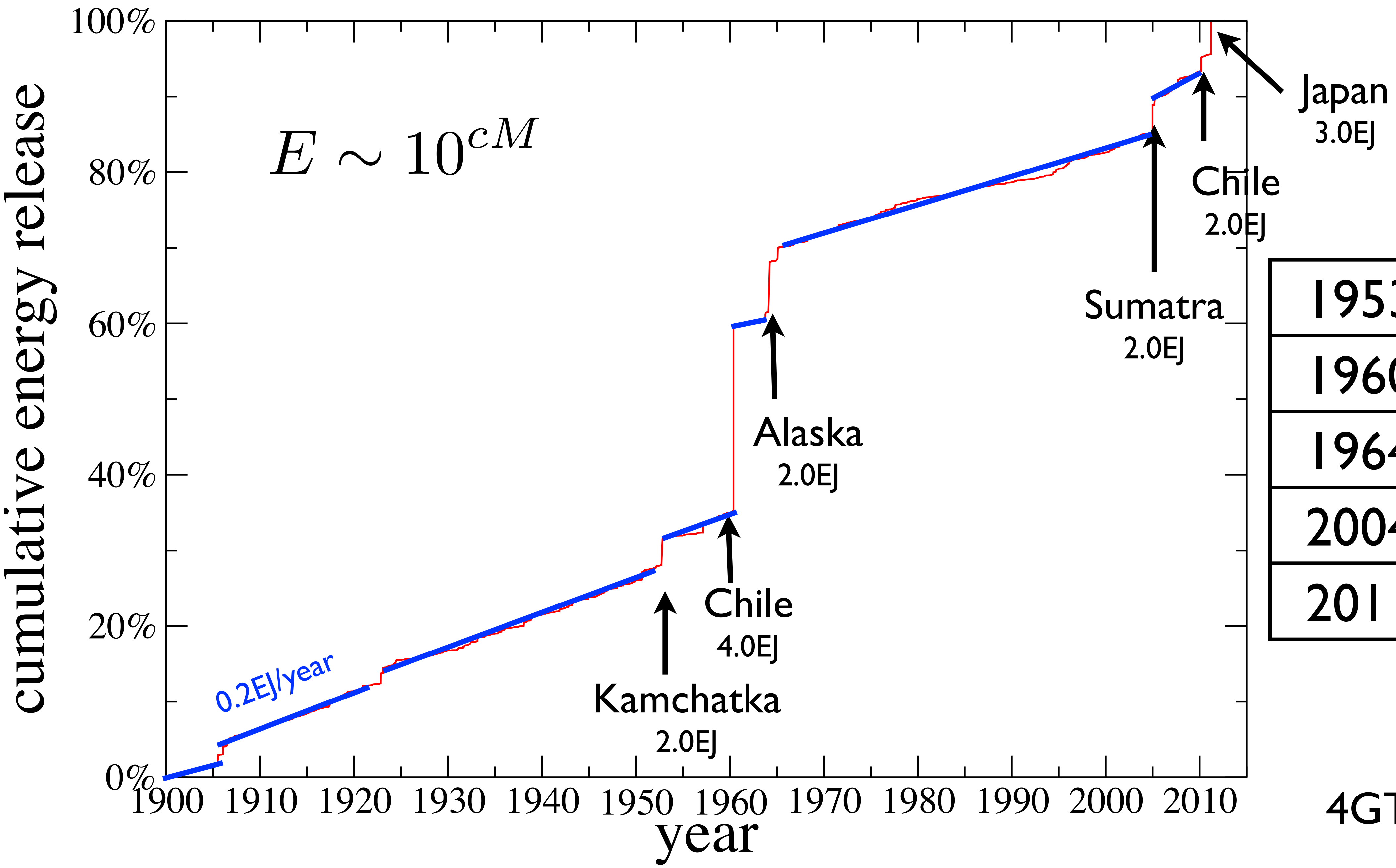


Plate Tectonics & Mantle Convection

Earth as an "earthquake machine"



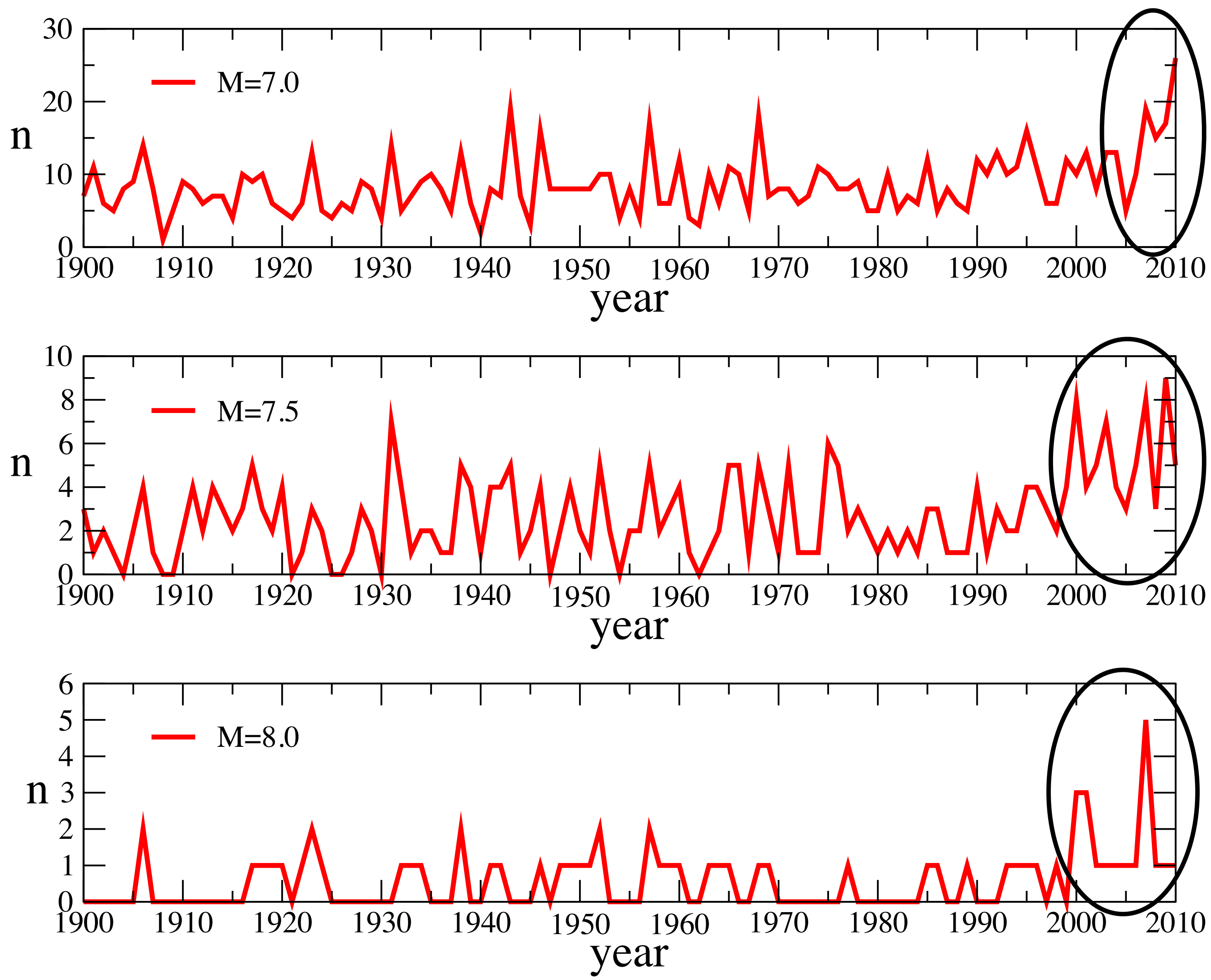
1953	9
1960	9.6
1964	9.2
2004	9
2011	9.1

4GT=1EJ

1. Few megaquakes account for a fraction of all energy release!
2. Two "clusters": 1960-1964, 2004-2010

Part I:
Statistics of the number of events a time interval

Uptick in large earthquakes?



Increase in number of large earthquakes, latest decade

correlations in time?

Questions

- Is uptick statistically significant?
- What is the likelihood of such an uptick?
- How to quantify such likelihoods?
- Is data complete? consistent?
- Role of aftershocks?

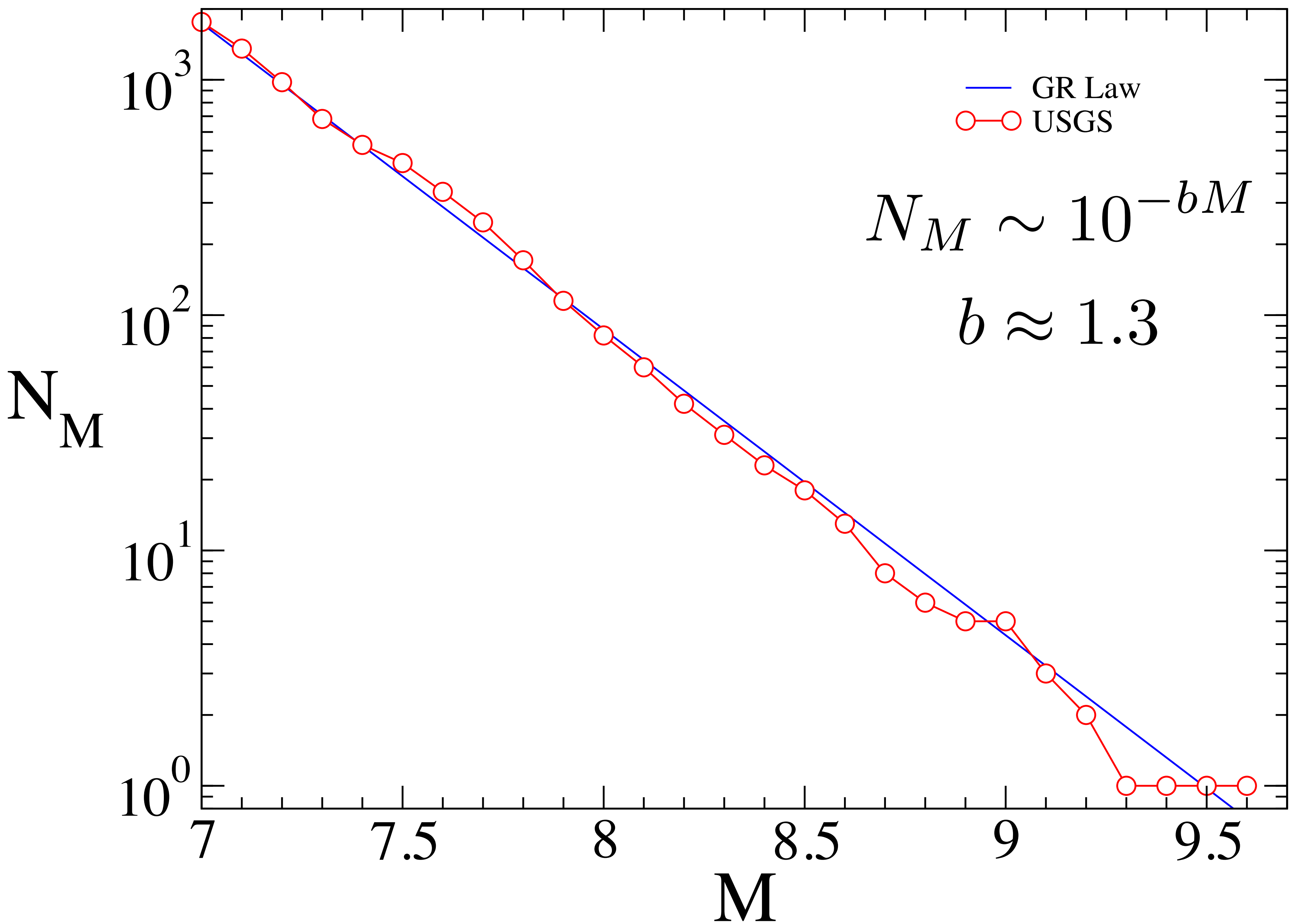
Are large earthquakes correlated in time?
Are large earthquakes completely random?

Lay 2010

Data

- Catalogs: USGS (PAGER)
- All known magnitude > 7.0 during 1900-2012
- Roughly 2000, 500, 100 magnitude >7.0, 7.5,8.0
- Dataset for M>7.0 is mostly complete
- Data is in format (t,M)=time, seismic moment magnitude
- Magnitude M = M_w surface wave magnitude

Gutenberg-Richter Law



Magnitude	Annual #
9-9.9	1/20
8-8.9	1
7-7.9	15
6-6.9	134
5-5.9	1300
4-4.9	~13,000
3-3.9	~130,000
2-2.9	~1,300,000

Rundle 89
Pacheco 92

Universal law, holds at all magnitudes even for the largest events

Poisson Distribution

- Assumes no correlations between events
- Completely characterized by average α
- Specified the probability P_n of observing n events in given time interval T (in months)

$$P_n = \frac{\alpha^n}{n!} e^{-\alpha}$$

- Unique feature: variance equals average

$$\langle n \rangle = \sum_{n=0}^{\infty} n P_n = \alpha \qquad V = \langle n^2 \rangle - \langle n \rangle^2 = \alpha$$

Use the random distribution to test for correlations

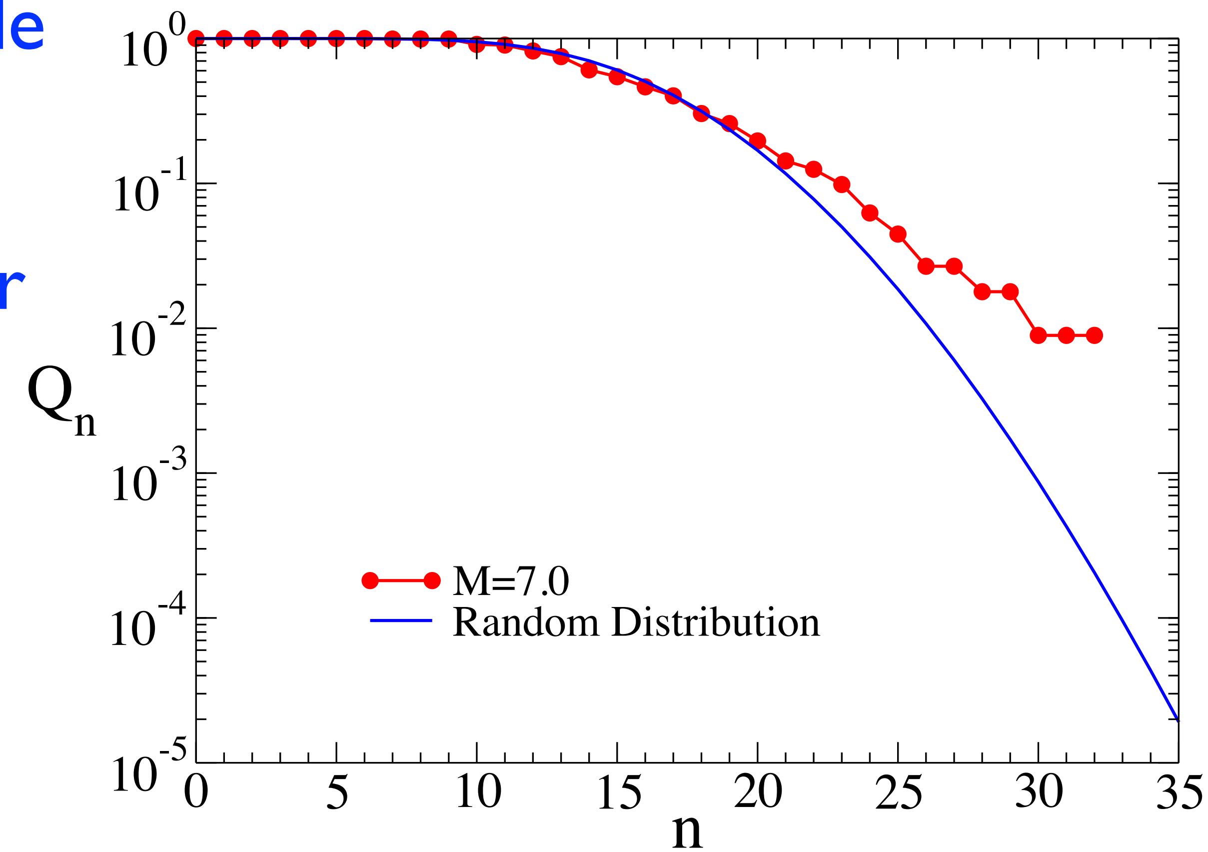
Overpopulated Tails?

- Event = an earthquake with magnitude larger than thresholds M
- Use cumulative probability Q_n that there are at least n events in one year

$$Q_n = \sum_{m=n}^{\infty} \frac{\alpha^m}{m!} e^{-\alpha}$$

- Use average from data

$$\alpha = 15.7$$



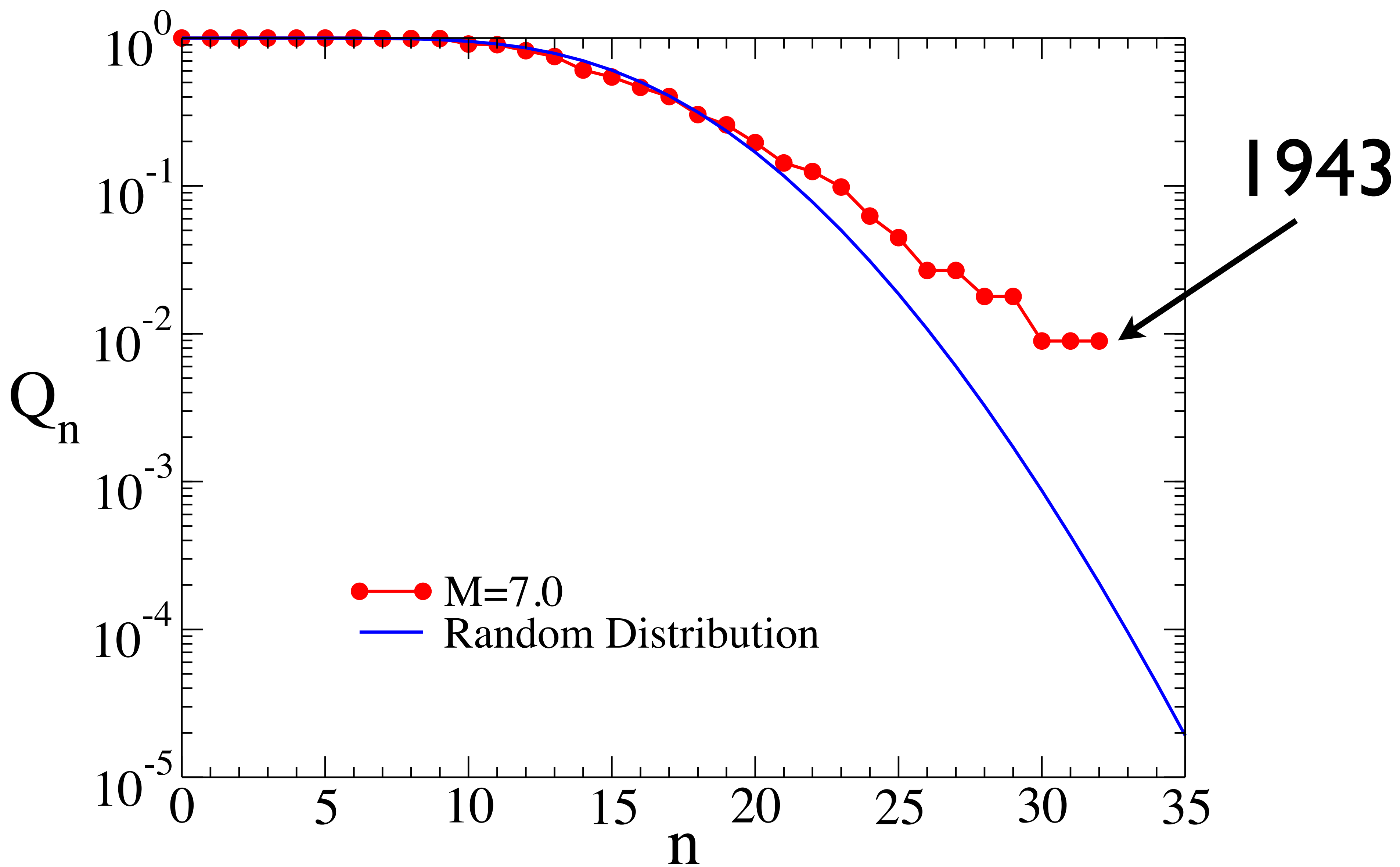
Observed frequency matches random distribution when $n < \alpha$

Observed frequency larger than random distribution when $n > \alpha$

Number of large earthquakes appears to be enhanced

Large earthquakes appear to be correlated in time

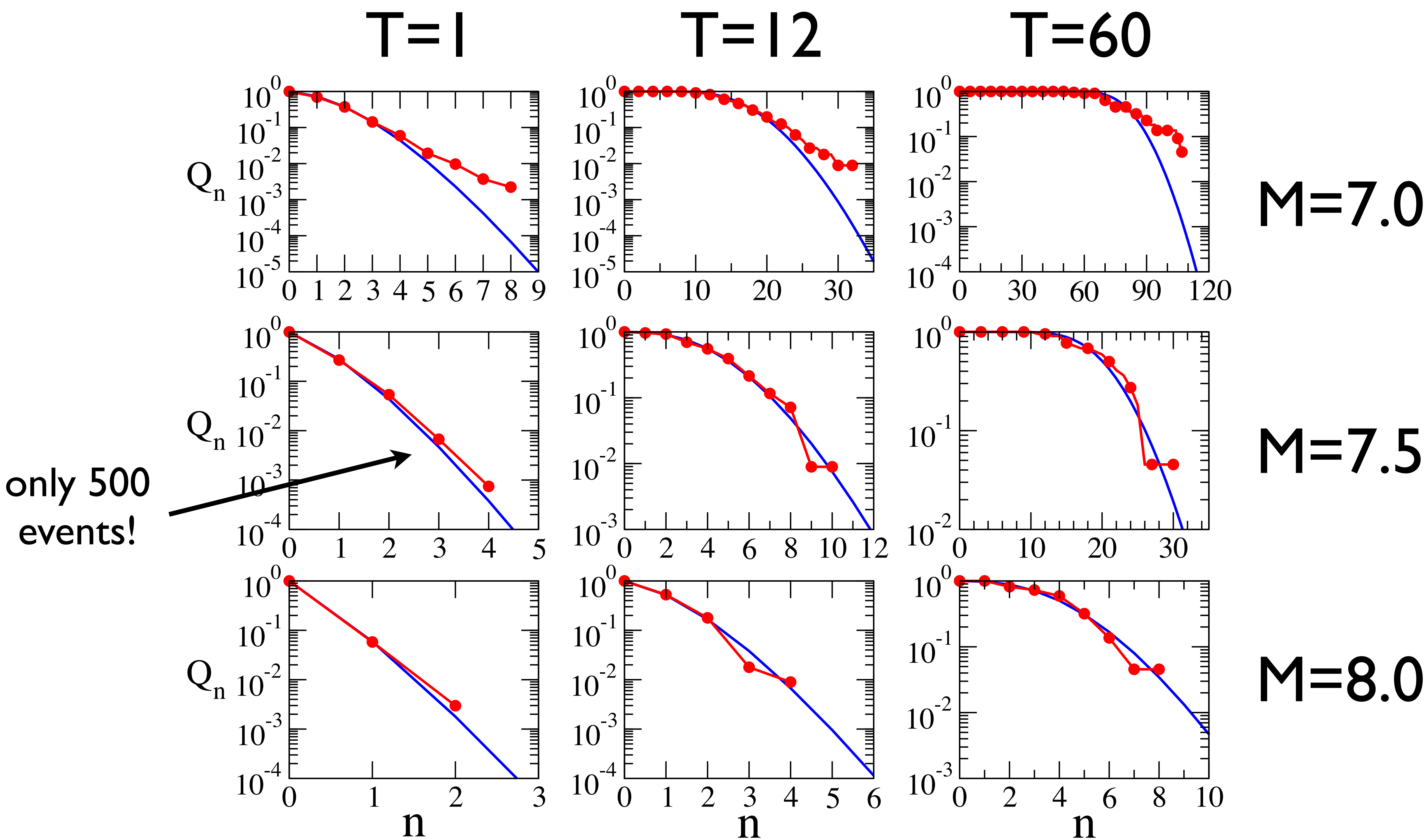
Overpopulated Tails



Distribution of number of events per year has an enhanced tail

0.02 = expected number of years with 32 events if record is random!

Dependence on threshold & time interval

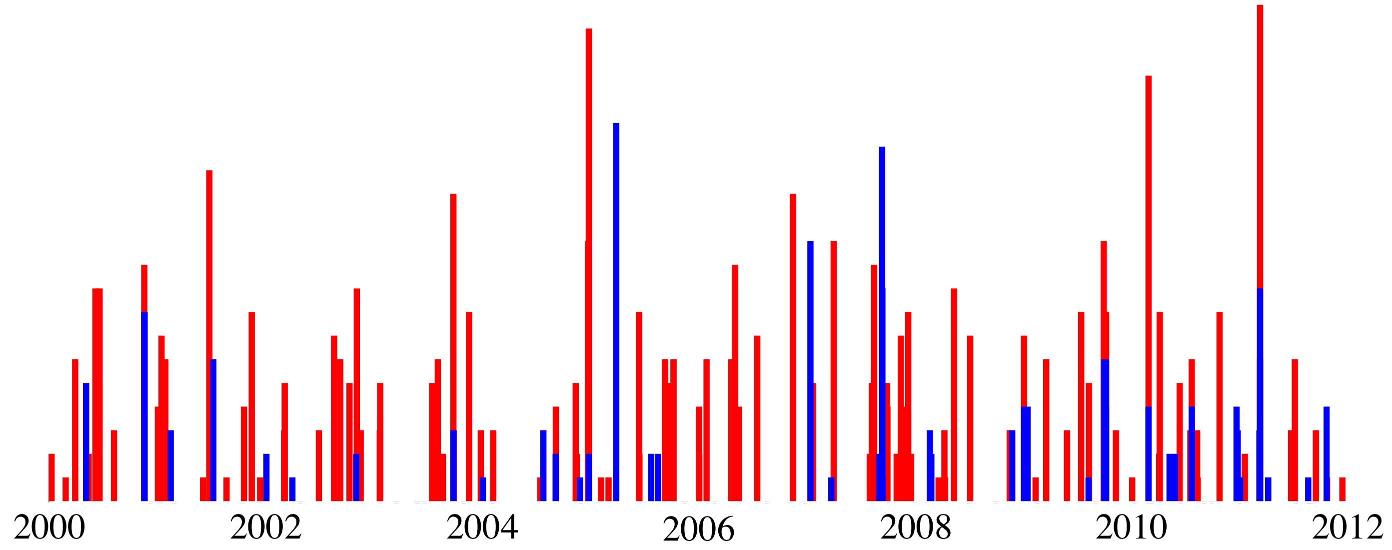


Overpopulation significant only at M=7.0

Attribute to <u>aftershocks</u>, at least for short intervals

Good agreement with random statistics otherwise

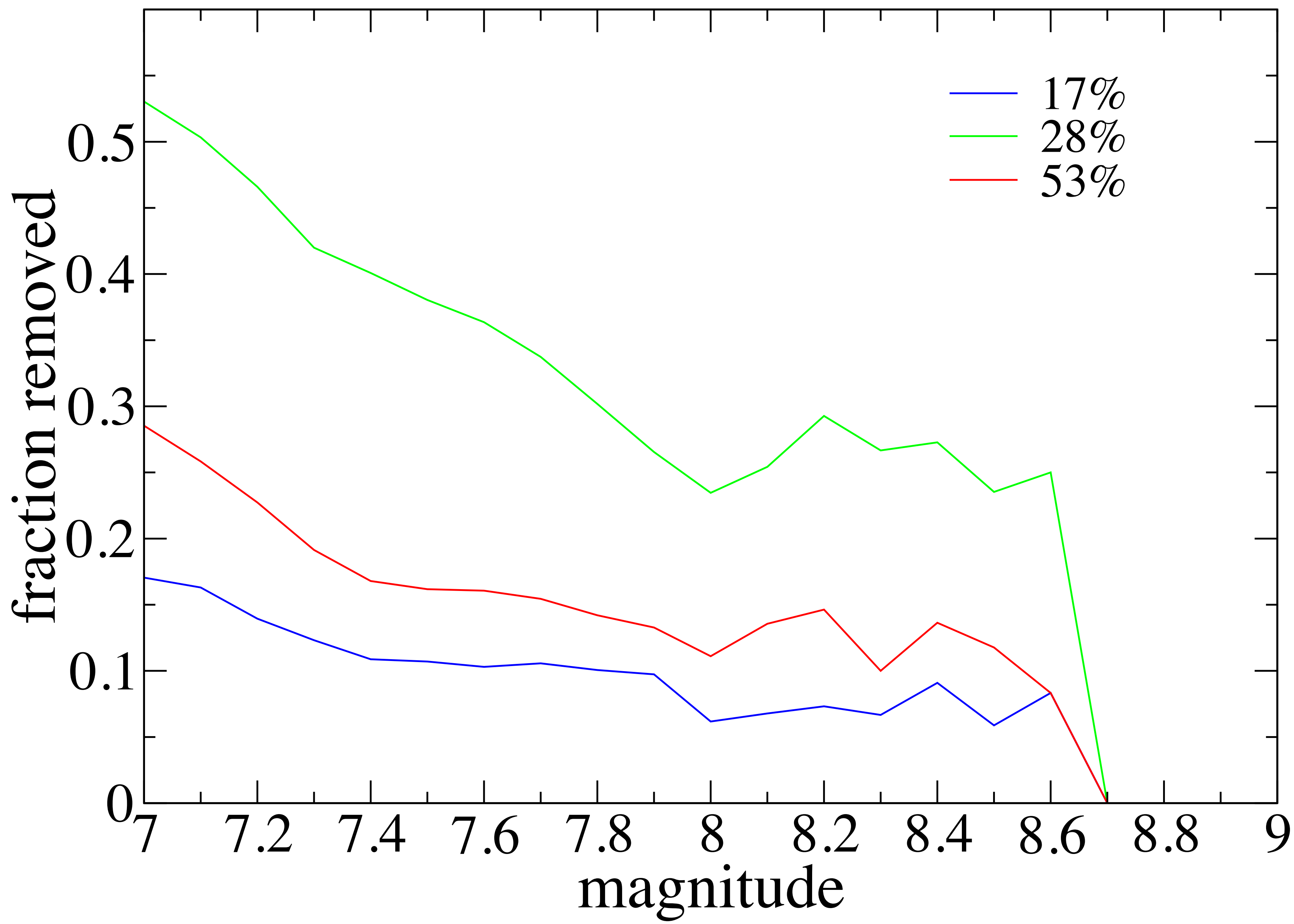
Aftershock removal



- Use standard procedure (Gardner & Knopoff 74)
- Flag events as aftershocks according to
  - Time window
  - Distance window ~ rupture length of shock
- Incomplete data
- Use empirical rupture length formula (Wells & Coppersmith 94)
- Vary strictness of procedure

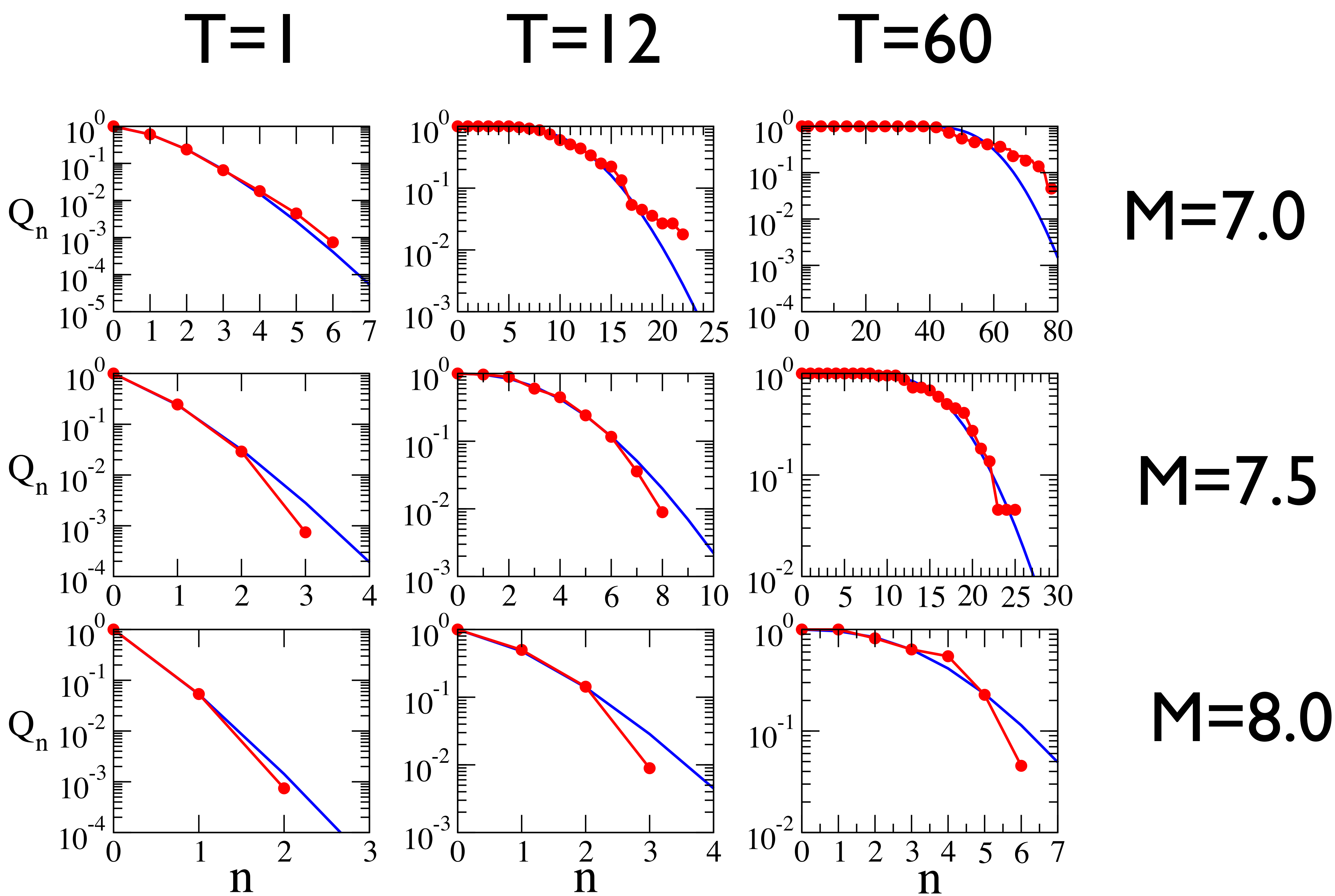
Results largely independent of details of aftershock removal procedure

How many aftershocks?



Use intermediate procedure

Aftershocks removed:
Dependence on threshold & time interval



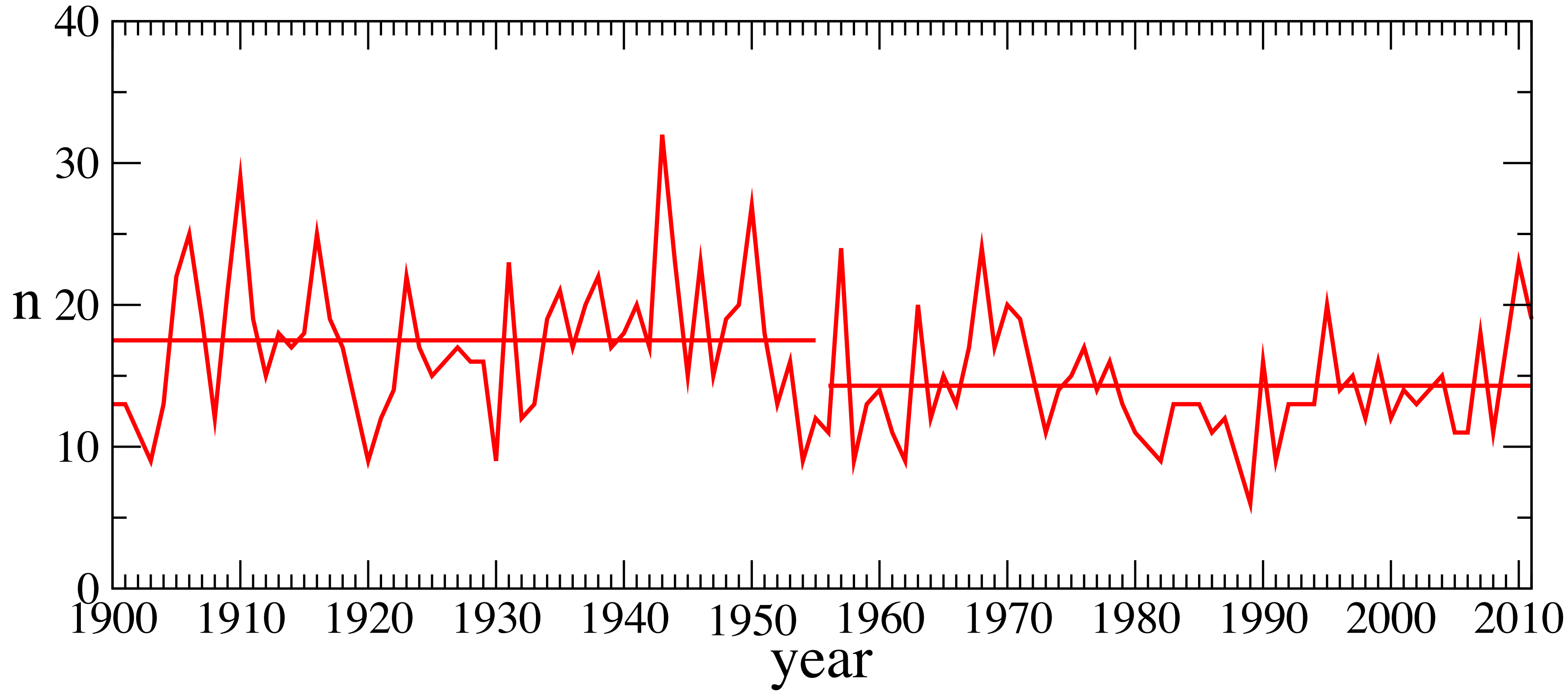
M=7, T=1 is now Poissonian

Overpopulation at M=7, T>12 persists

Underpopulation due to overzealous aftershock removal

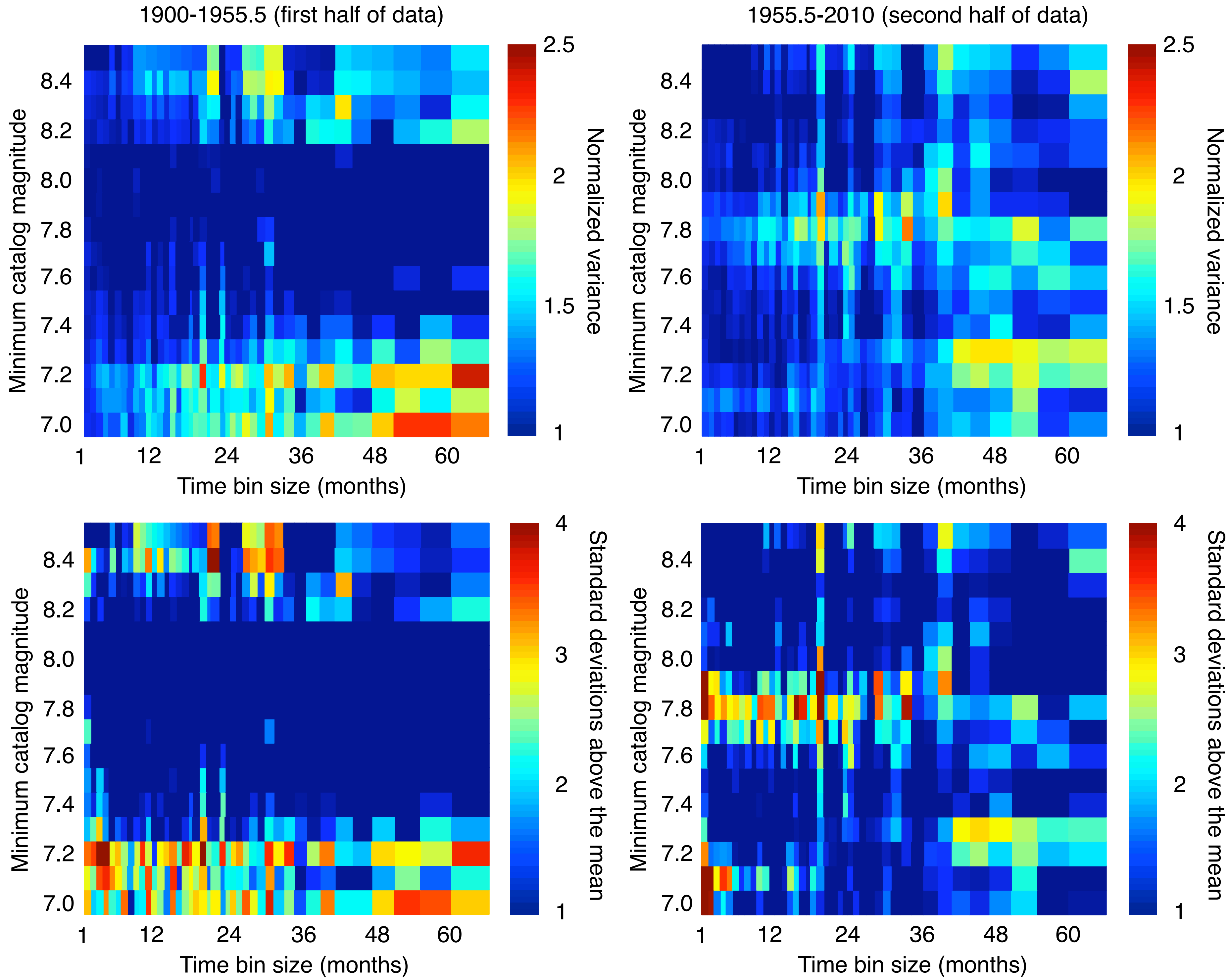
Comparing first and second halves of century

17.5 events/year (1900-1955) vs 14.3 events/year (1955-2011)



Rate mismatch suggests difference in measurement or different methodology

Mainshocks and Aftershocks



Separately, each 50 year record is random

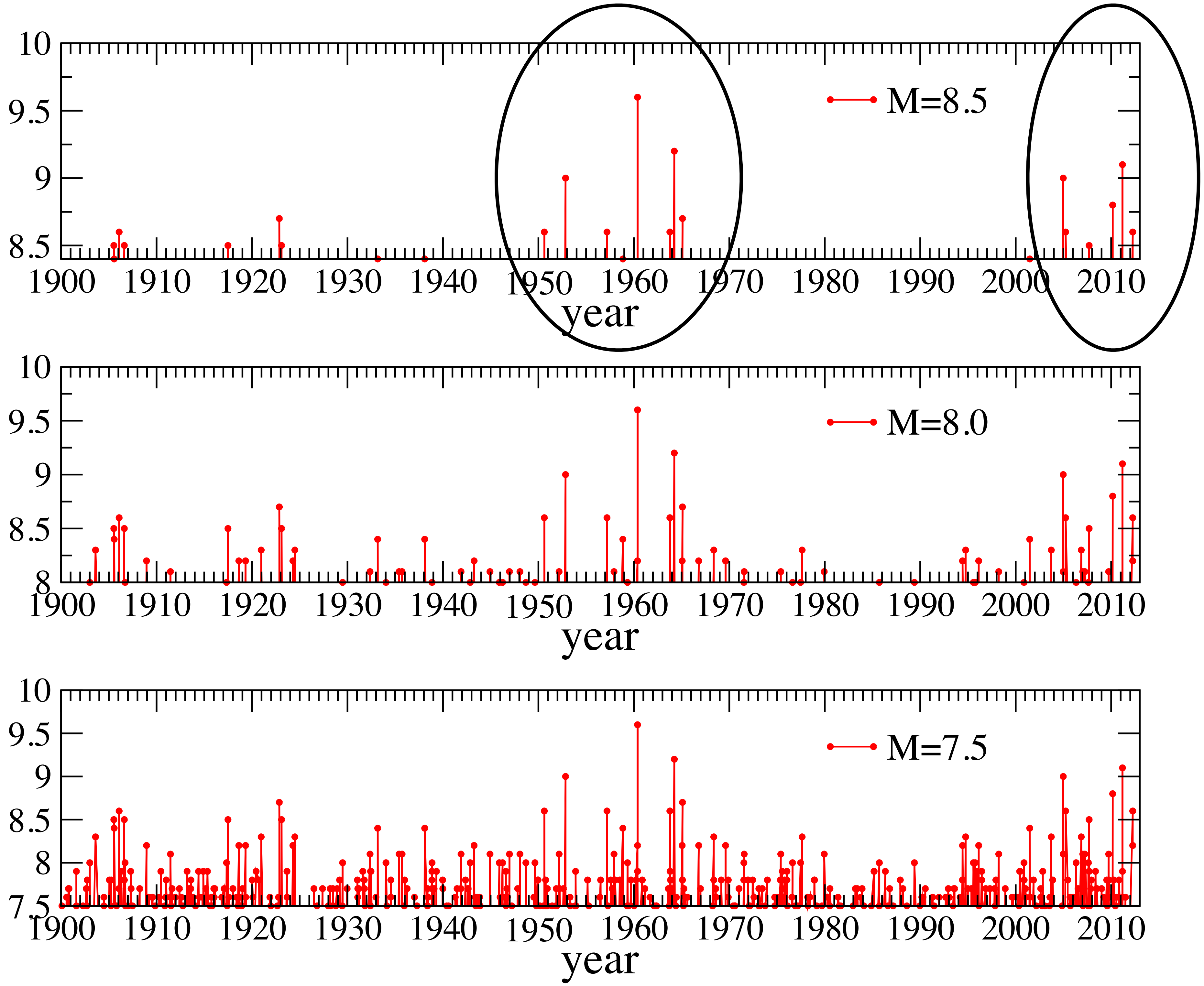
Summary I

- Number of events in a time interval
- Analysis of probability distribution function
- Megaquakes largely consistent with random statistics
- Aftershock removal not crucial
- Aftershock removal useful at small time intervals
- No significant deviations from random process
- Suggests that large earthquakes are random in time
- Results reinforce several recent studies

Michaels 11
Shearer & Stark 11

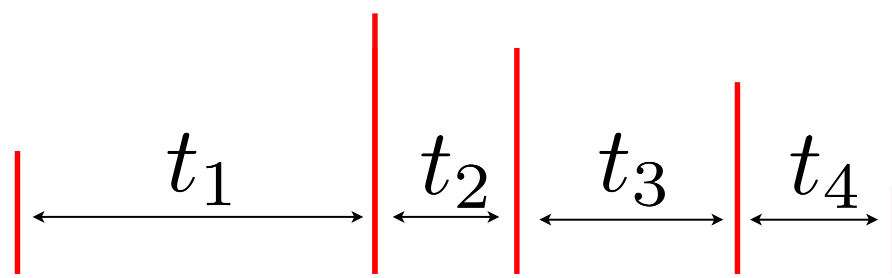
Part II:
Statistics of the time interval between events

A second look at the largest events



Focus on even larger magnitudes

Recurrence time statistics

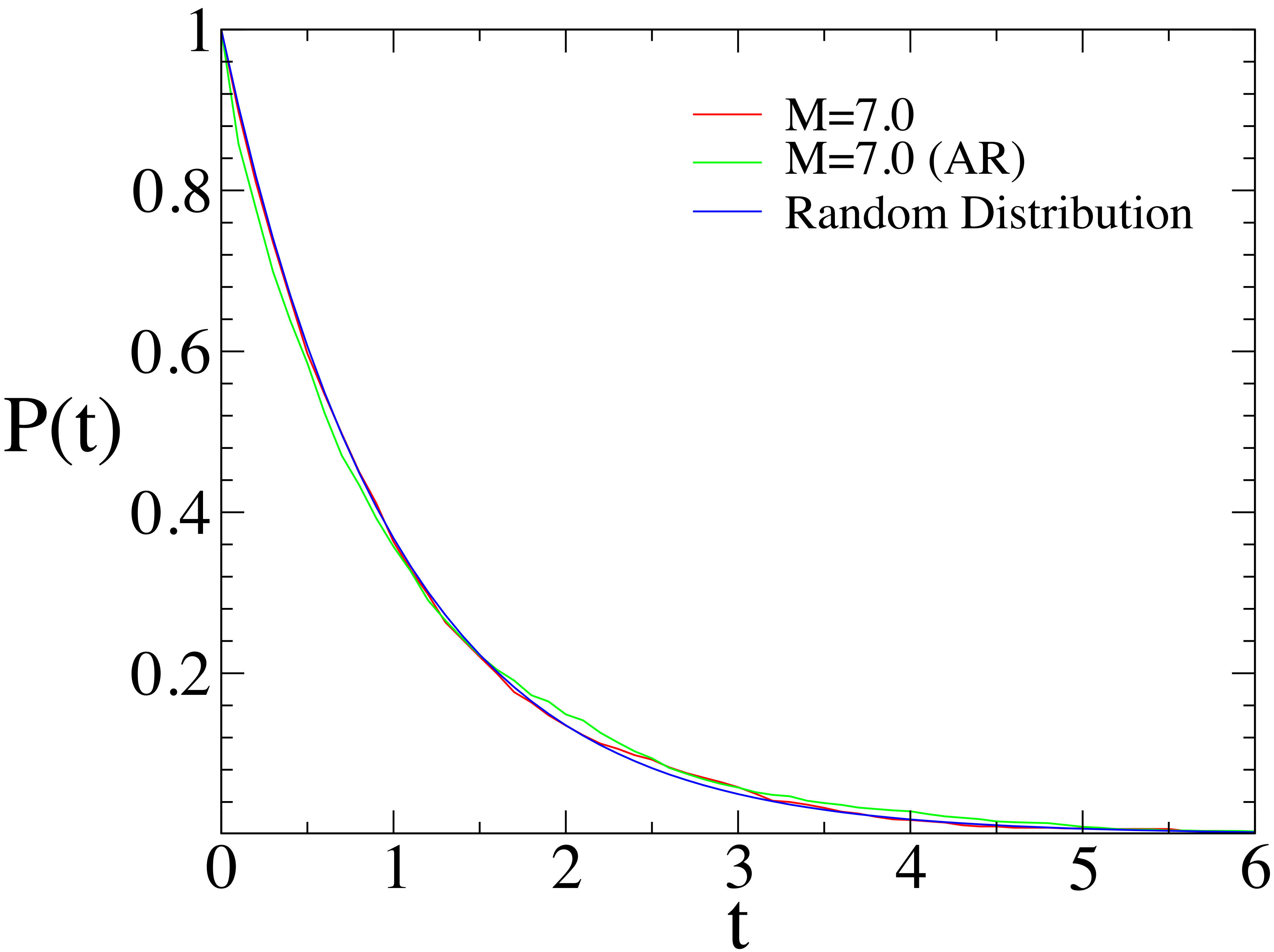


- Measure time between two successive events
- Heavily used in earthquake analysis
- Random Distribution: <u>both</u> distribution of recurrence times, and cumulative distribution are exponential

$$p(t) = \tau^{-1} e^{-t/\tau} \quad P(t) = \int_t^\infty ds\, P(s) = e^{-t/\tau}$$

A. Michaels 11

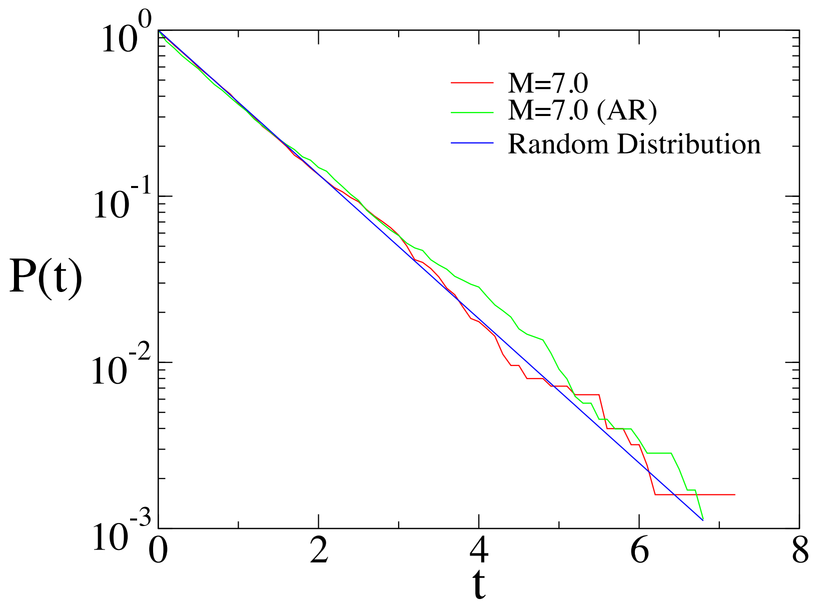
Recurrence time statistics



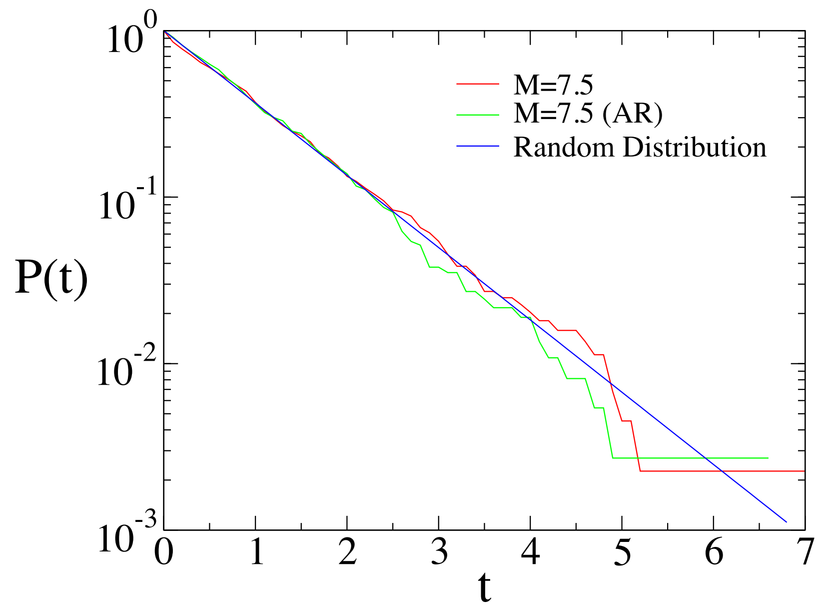
Very good agreement with random distribution!

Extreme Statistics

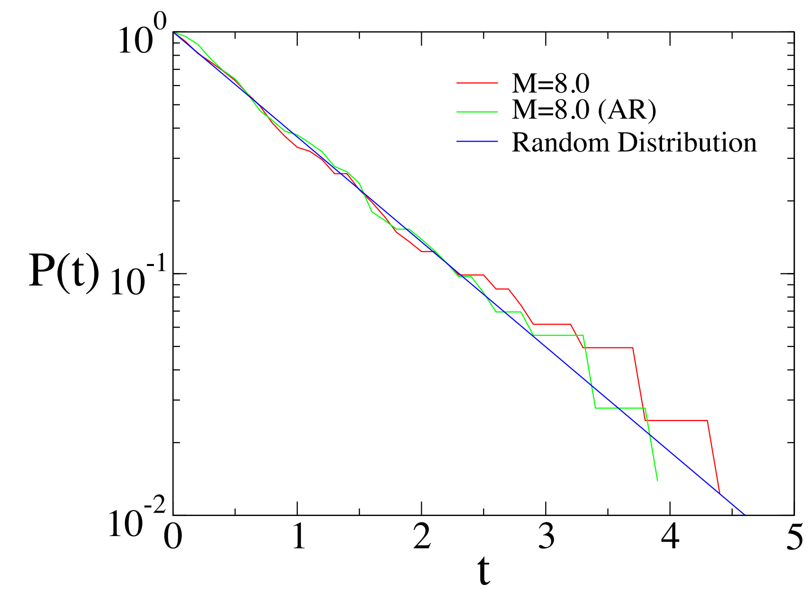
$\langle t \rangle = 0.76$ months



$\langle t \rangle = 3.03$ months



$\langle t \rangle = 16.4$ months



- Quantify statistical significance?

Variance

- Again, the normalized variance equals 1!

$$V = \langle t^2 \rangle - \langle t \rangle^2 = \langle t \rangle = 1$$

M	V	V
7	1.55	1.03
7.5	1.07	0.89
8	1	0.84

Overzealous AR?

Normalized variance

- Scalar quantity

$$V = \frac{\langle t^2 \rangle - \langle t \rangle^2}{\langle t \rangle^2}$$

- Simplest measure of fluctuations

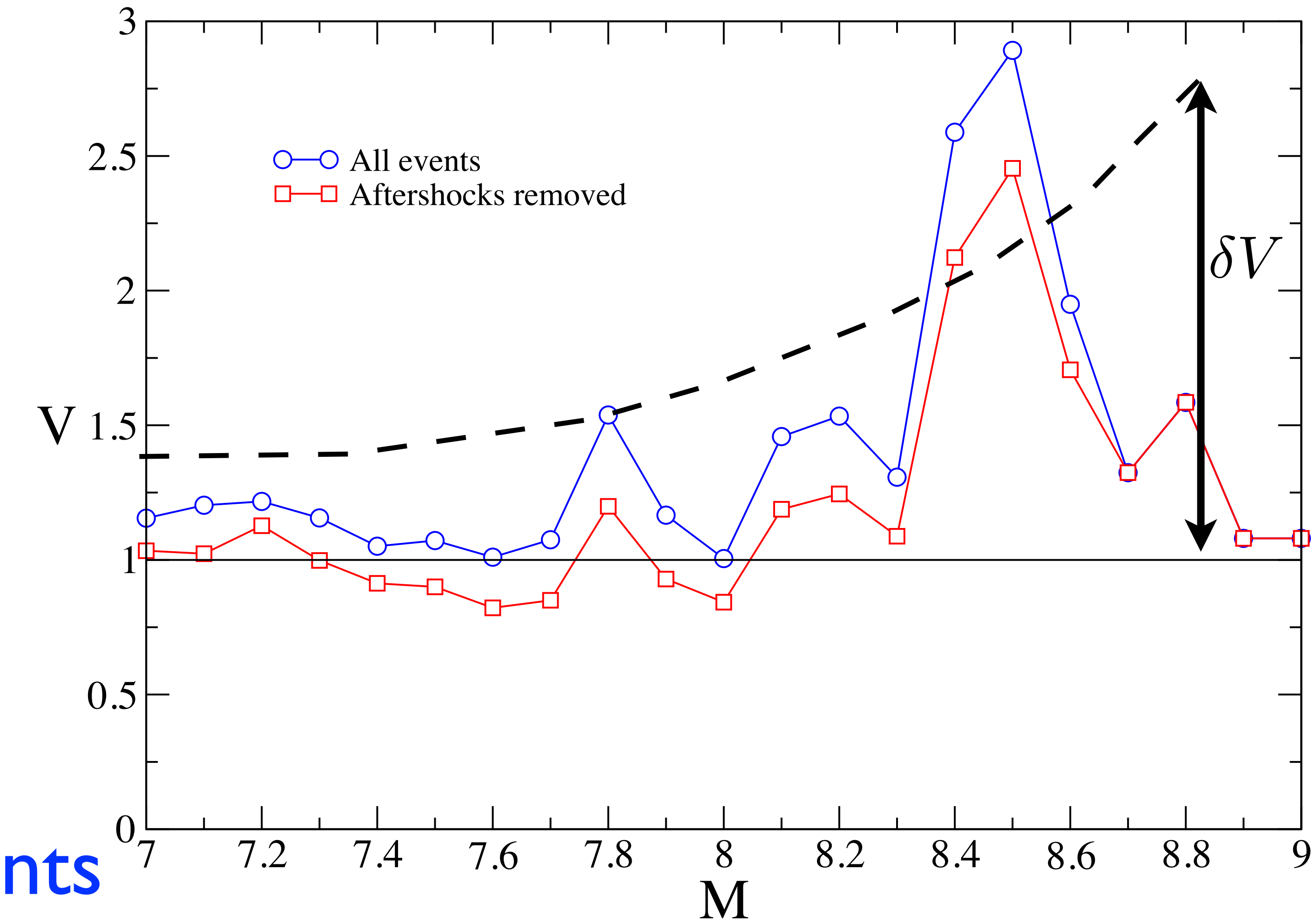
Random events	$V \approx 1$
Correlated events	$V \gg 1$

- Dependence on number of events

$$\langle V^2 \rangle - \langle V \rangle^2 = \frac{2(N-1)(4N-3)}{N^3}$$

- Must take into account variability "envelope"

$$\delta V \sim N^{-1/2}$$



Large variance for M~8.5
is it statistically significant?

Statistics of the Variance

- Consider N independent identically distributed variables, drown from the probability distribution $P(t)$
- Measure the variance from the dataset $\{t_1, t_2, \ldots, t_N\}$

$$V = \frac{t_1^2 + t_2^2 + \cdots + t_N^2}{N} - \left(\frac{t_1 + t_2 + \cdots + t_N}{N}\right)^2$$

- Moments of the variance given by cumulants of the distribution

$$\langle V \rangle = \frac{N-1}{N}\,\kappa_2 \qquad \langle V^2 \rangle - \langle V \rangle^2 = \frac{(N-1)\left[(N-1)\kappa_4 + 2N\kappa_2^2\right]}{N^3}$$

$$\kappa_2 = M_2 - M_1^2 \qquad \kappa_4 = M_4 - 4M_3M_1 - 3M_2^2 + 12M_2M_1^2 - 6M_1^4$$

Variance of the variance
accounts for small number of events

Number of standard deviations

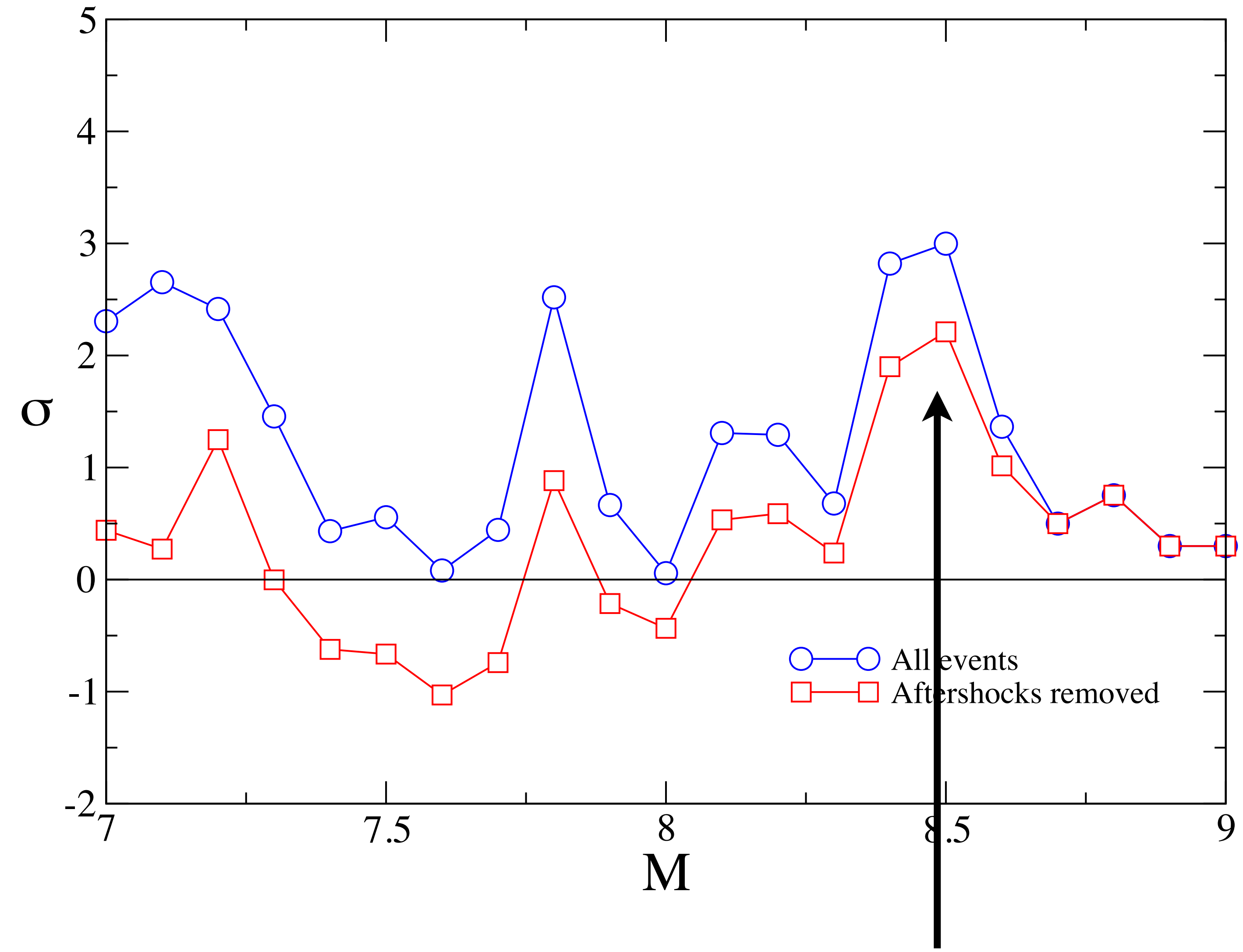
- Scalar quantity

$$\sigma = \frac{V - \bar{V}}{\delta V}$$

- Roughly normal distribution
- Bell curve gives probabilities

1	2	3	4
0.31	4.55E-02	2.7E-03	6.33E-05

- To account for deviations from Gaussian distribution, use synthetic catalogs adhering to random statistics

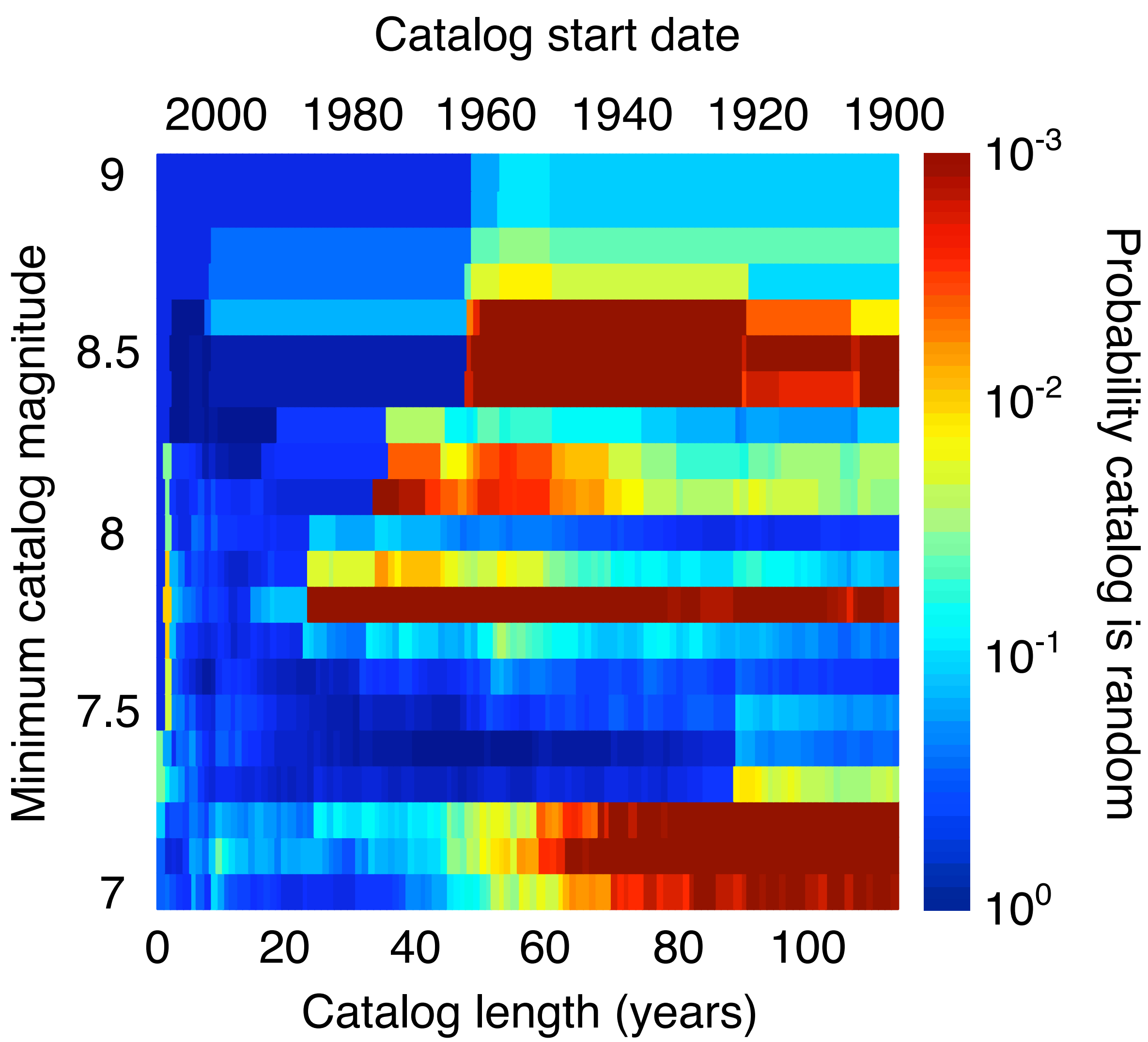


large variance for M~8.5 is statistically significant!

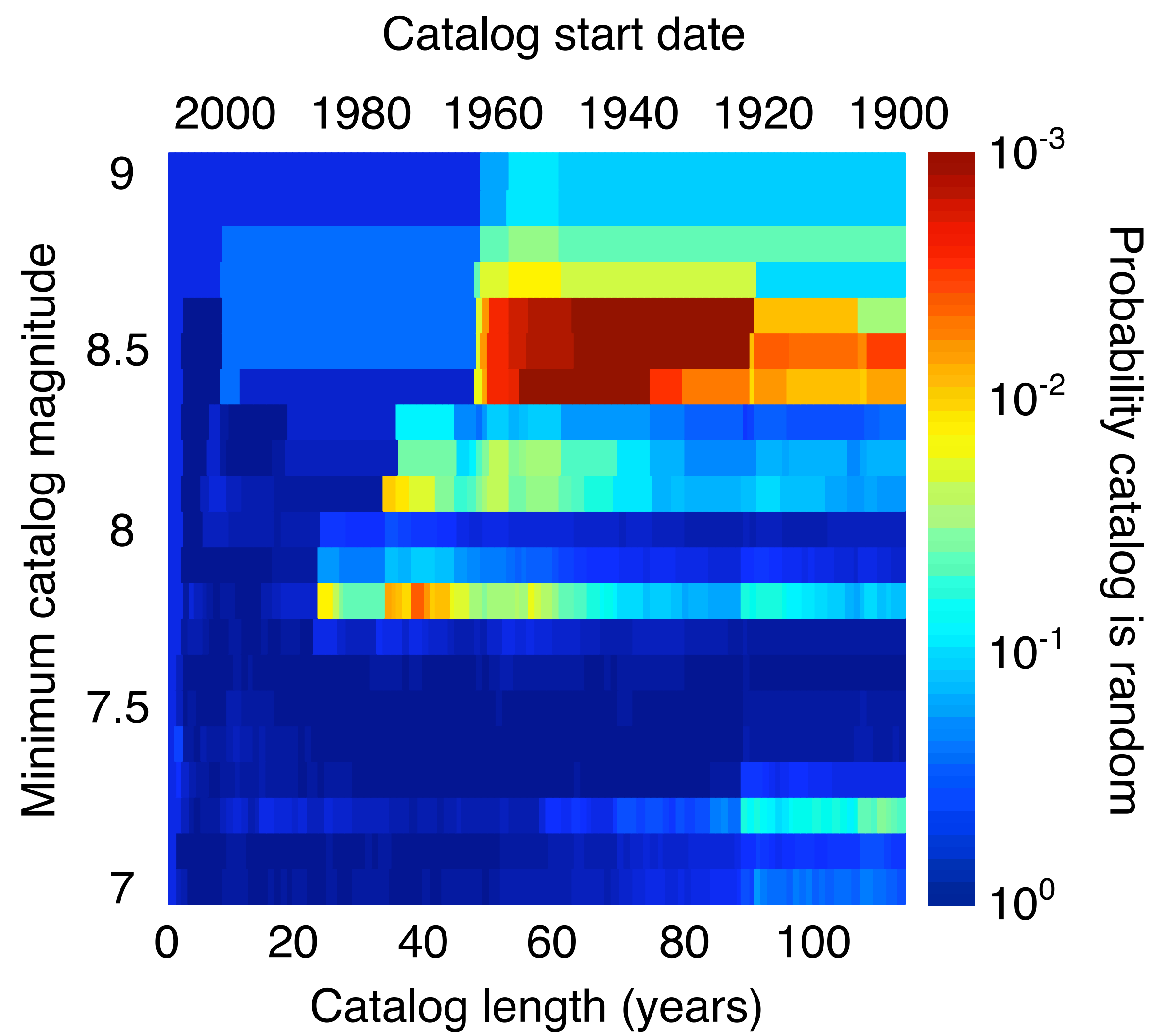
Statistically significant deviation from Poisson statistics

Random process probabilities

All events



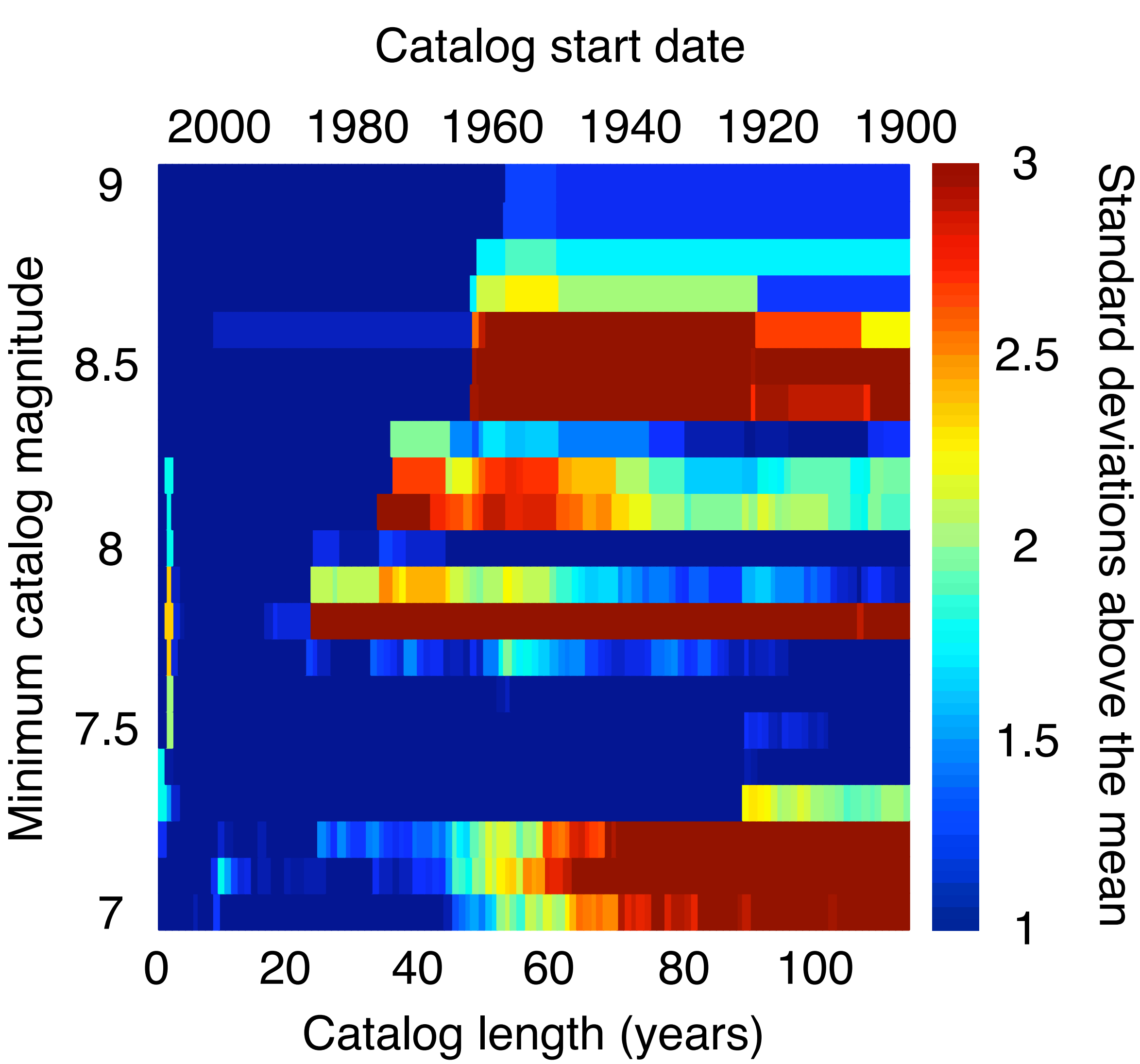
Aftershocks removed



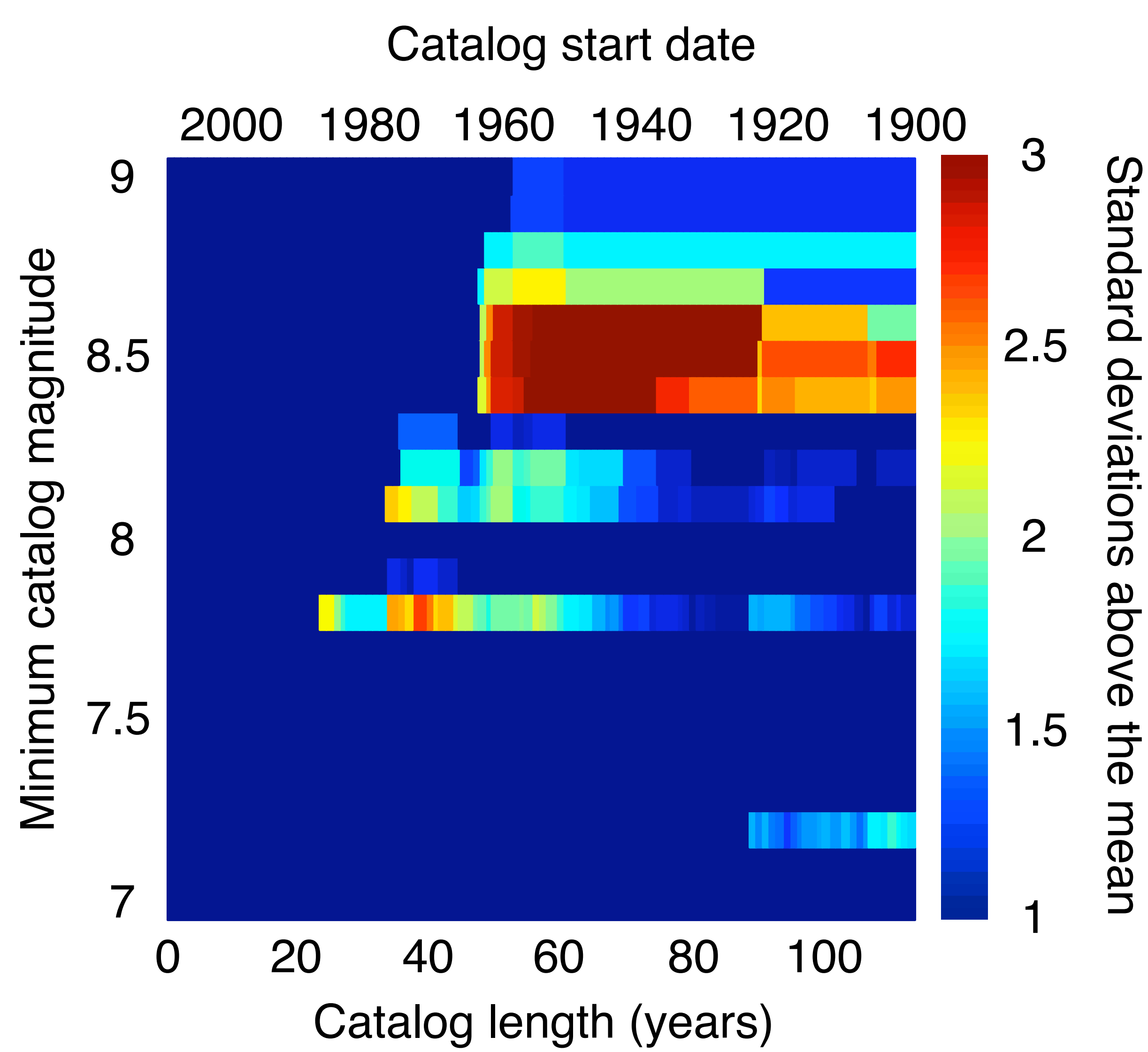
M=8.4-8.6, 1950-2012, with/without aftershocks evidence for deviation from random behavior

Number of standard deviations

All events

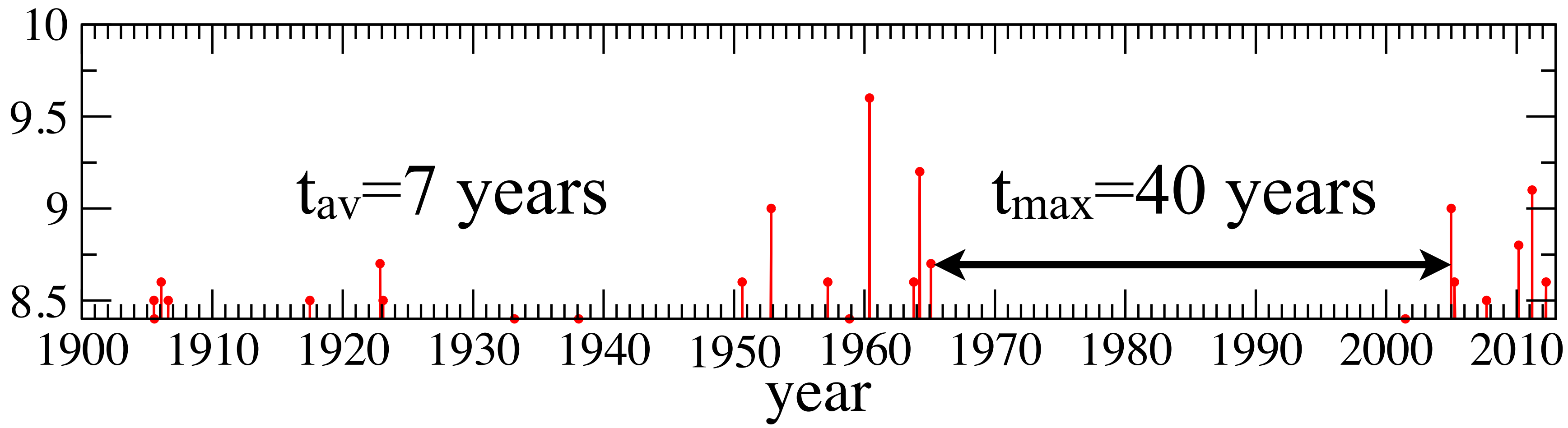


Aftershocks removed



M=8.4-8.6, 1950-2012, with/without aftershocks evidence for deviation from random behavior

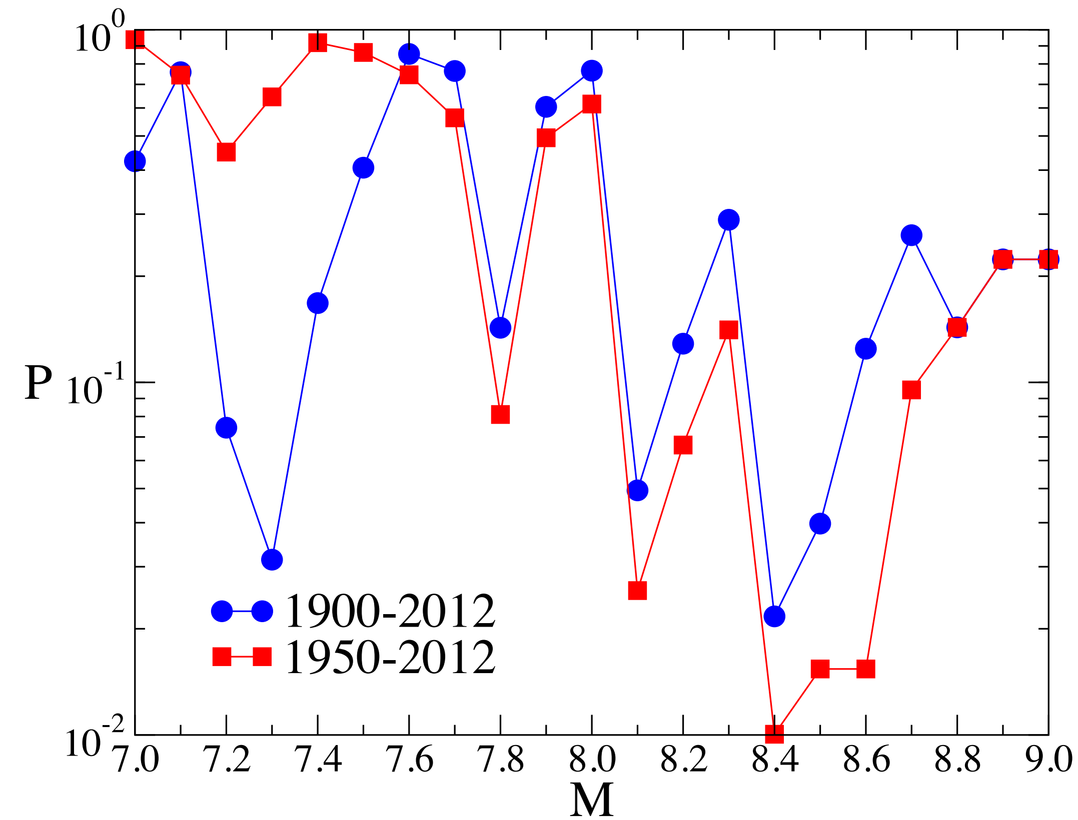
Maximal recurrence time



- Is the largest gap between events anomalously large?
- Probability of maximal gap for uncorrelated events

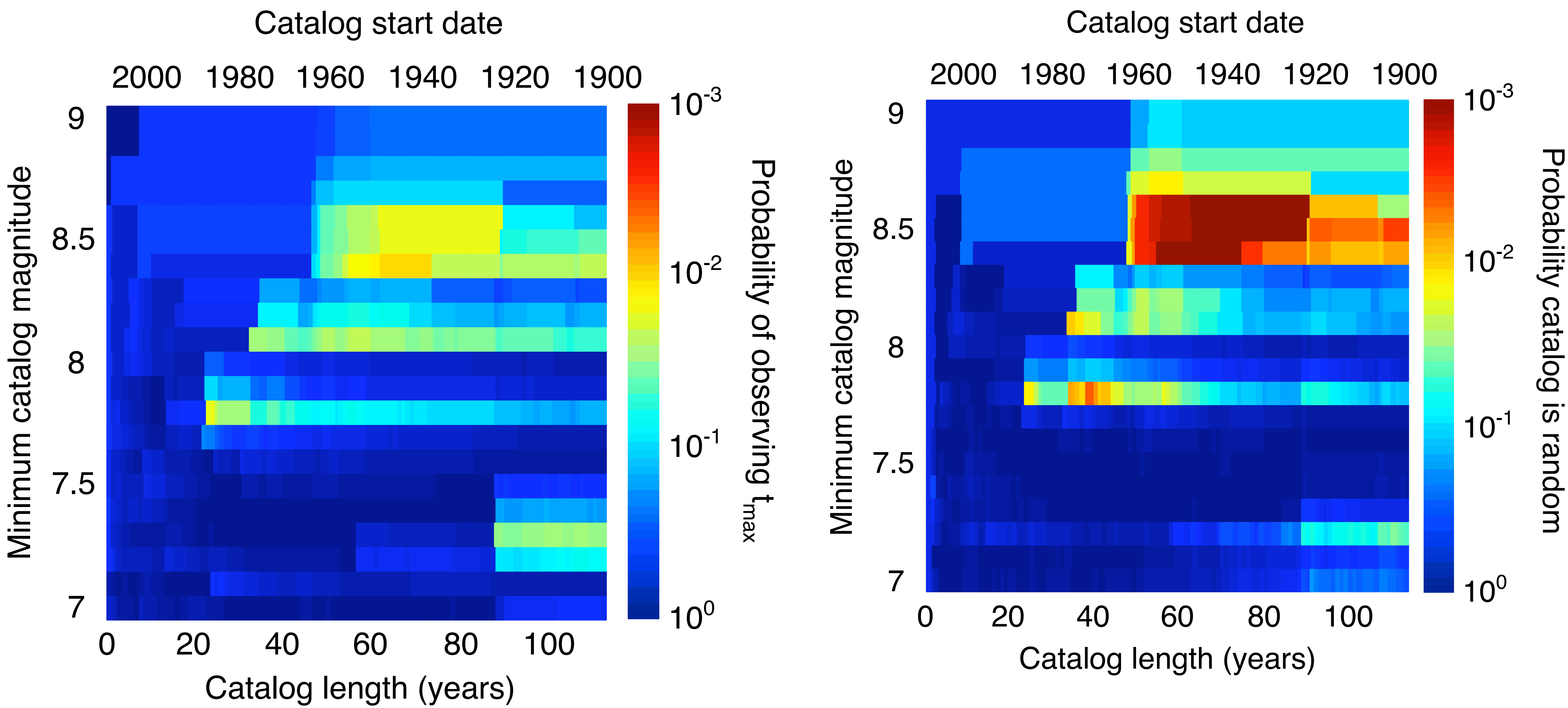
$$P_{\max} = 1 - \left(1 - e^{-t_{\max}/t_{\rm av}}\right)^N$$

- Ingredients: number of events, average time, maximal time



large gap for M~8.5 is anomalously large!

Largest gap vs. variance



Probabilities for maximal gap & variance consistent

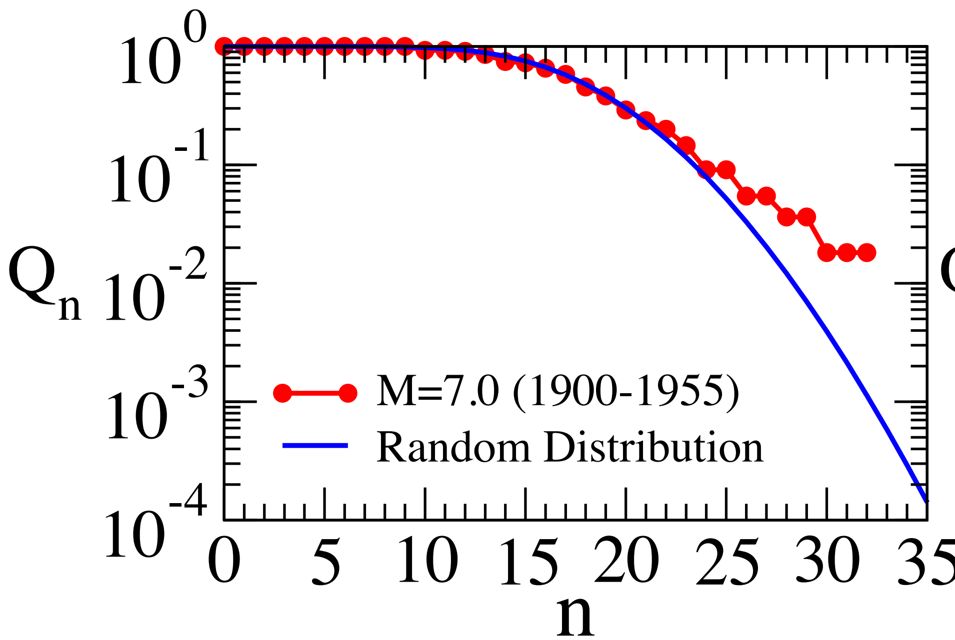
Largest recurrence times responsible for anomalous variance!

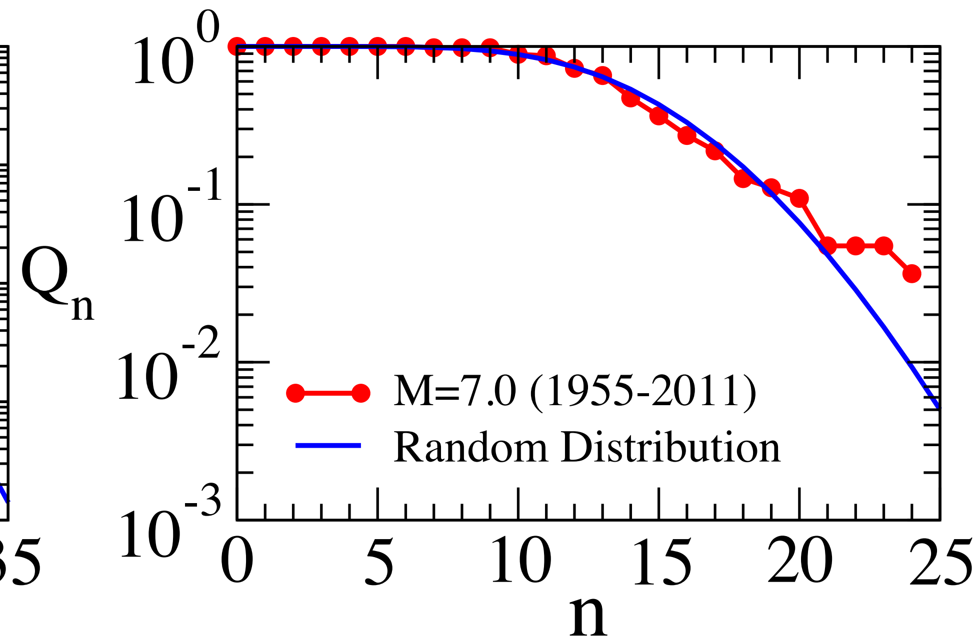
Summary II

- Recurrence time: transparent & convenient measure
- Statistics of the variance: basic measure of fluctuations
- Largely consistent with a random process
- Anomalies found for most massive events (M>8.5)
- Anomalously large quiescent periods responsible for anomalously large variance
- Reinforce recent results Bufe & Perkins 05, 11
- Can be used on smaller magnitude data
- Can be used on local data

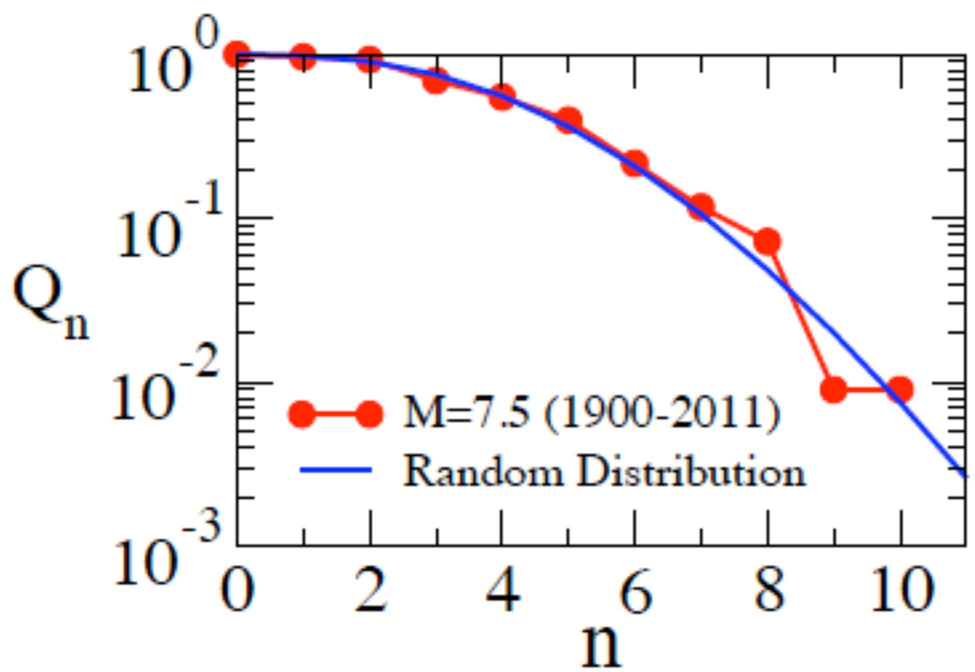
Robustness

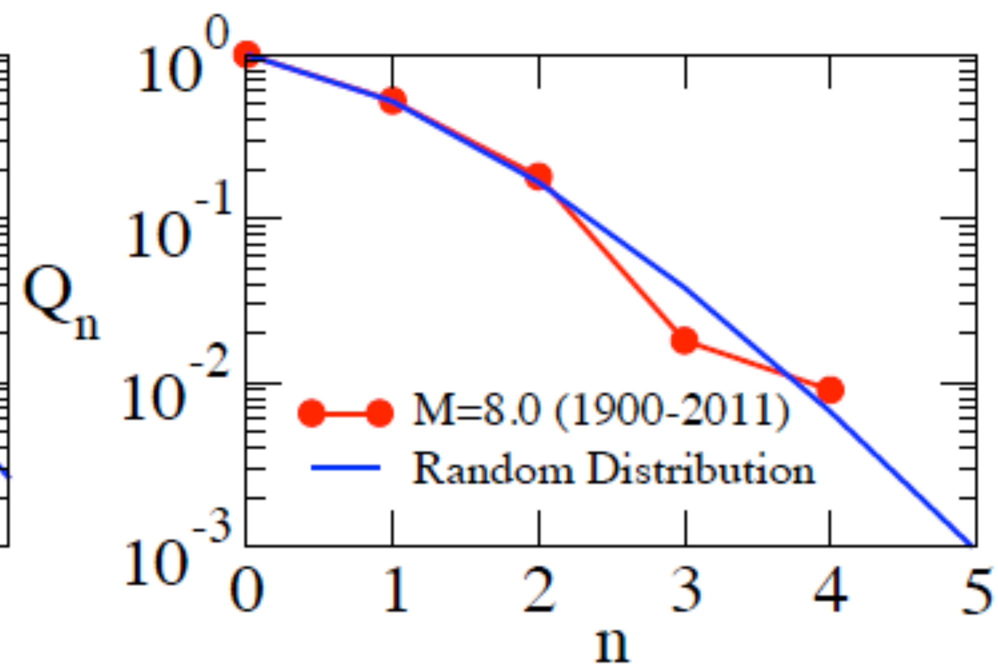
1900-1955 vs 1955-2011





M=7.5 and M=8.0



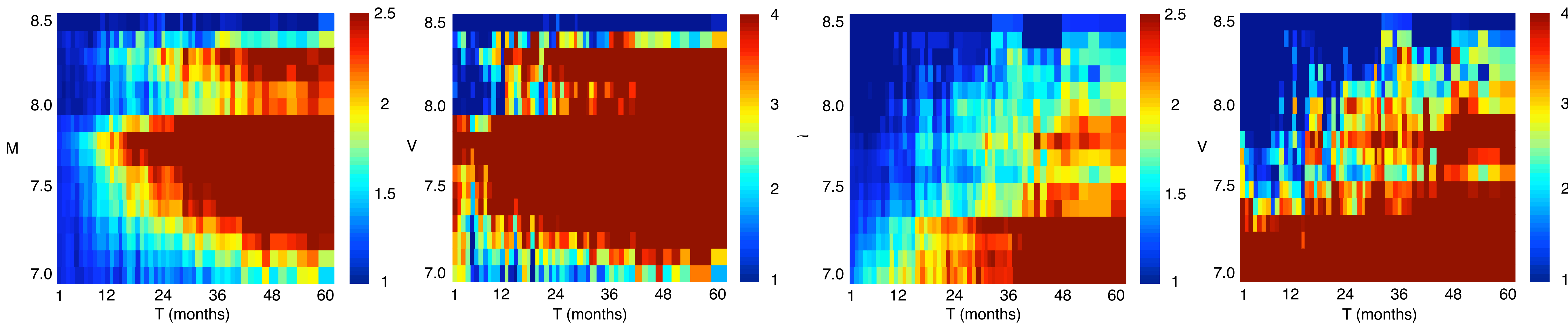


Overpopulation robust for M=7.0, weak for M=7.5, 8.0

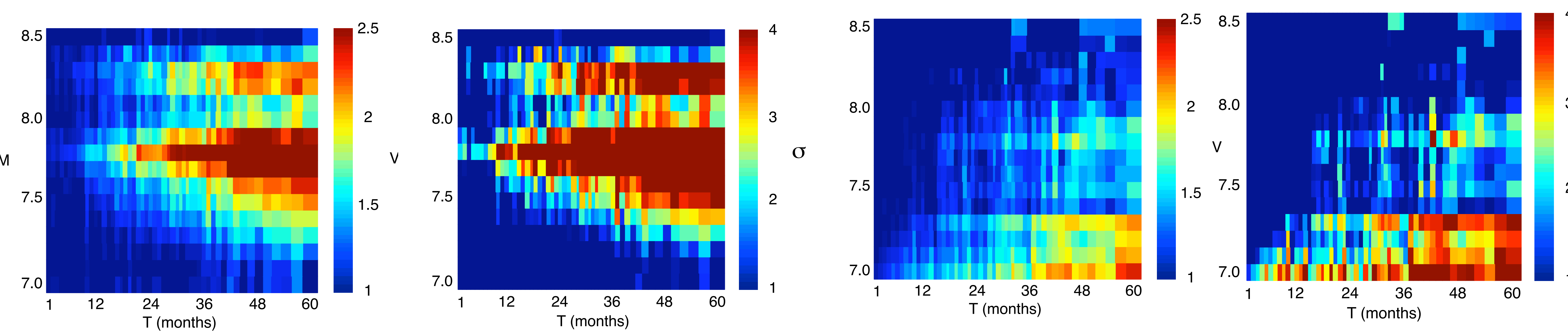
Different Catalogs

NOAA (1100 events) Pacheco-Sykes (900 events)

Mainshocks & Aftershocks



Mainshocks only



Strong deviation Moderate deviation

Questions

- Is the evidence for clustering statistically significant?
- How do we answer this question?

  ➡ Compare with Random Catalogs

- Is data sufficient? complete? consistent?

  ➡ Generate Synthetic Catalogs

- Role of aftershocks?

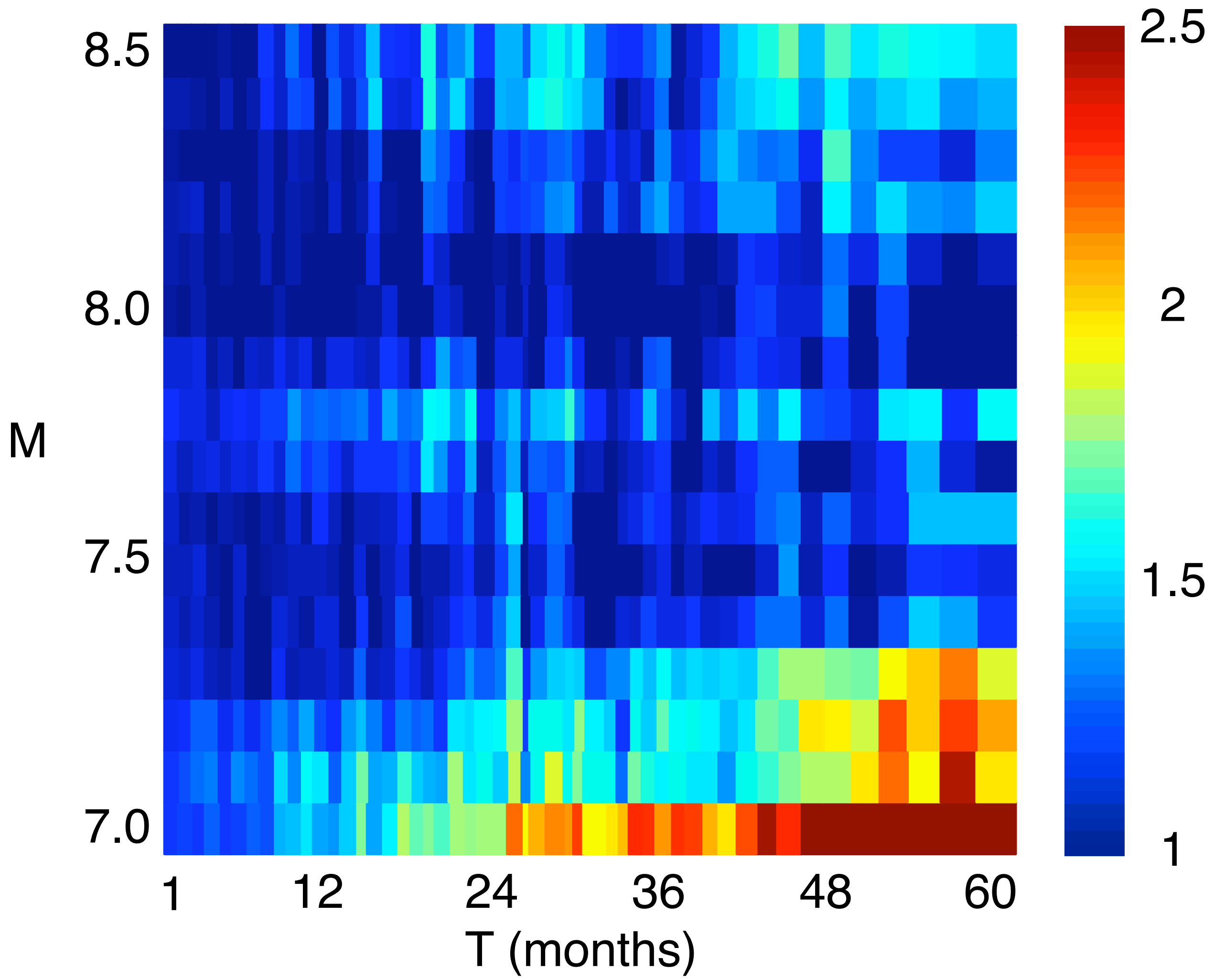
  ➡ Remove Aftershock (“decluster”)

Michaels 2010,Lay 2010

Normalized Variance

$$V = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle}$$

Random Distribution $V \approx 1$
Overpopulated Tail $V \gg 1$



Red= Overpopulated Tail

Blue= Random Distribution?

Overpopulation for M<7.3, T>24

Is this overpopulation Statistically Significant?

Synthetic Catalogs

- Generate huge number (10^6) of synthetic catalogs
- Catalogs match number of events (399 7.0, 375 7.1, 294 7.2,...)
- Measure the expected variance (very close to 1) and the variance of the variance

$$V \approx 1 \pm \delta V$$

- Represent the observed variance using # of standard deviations

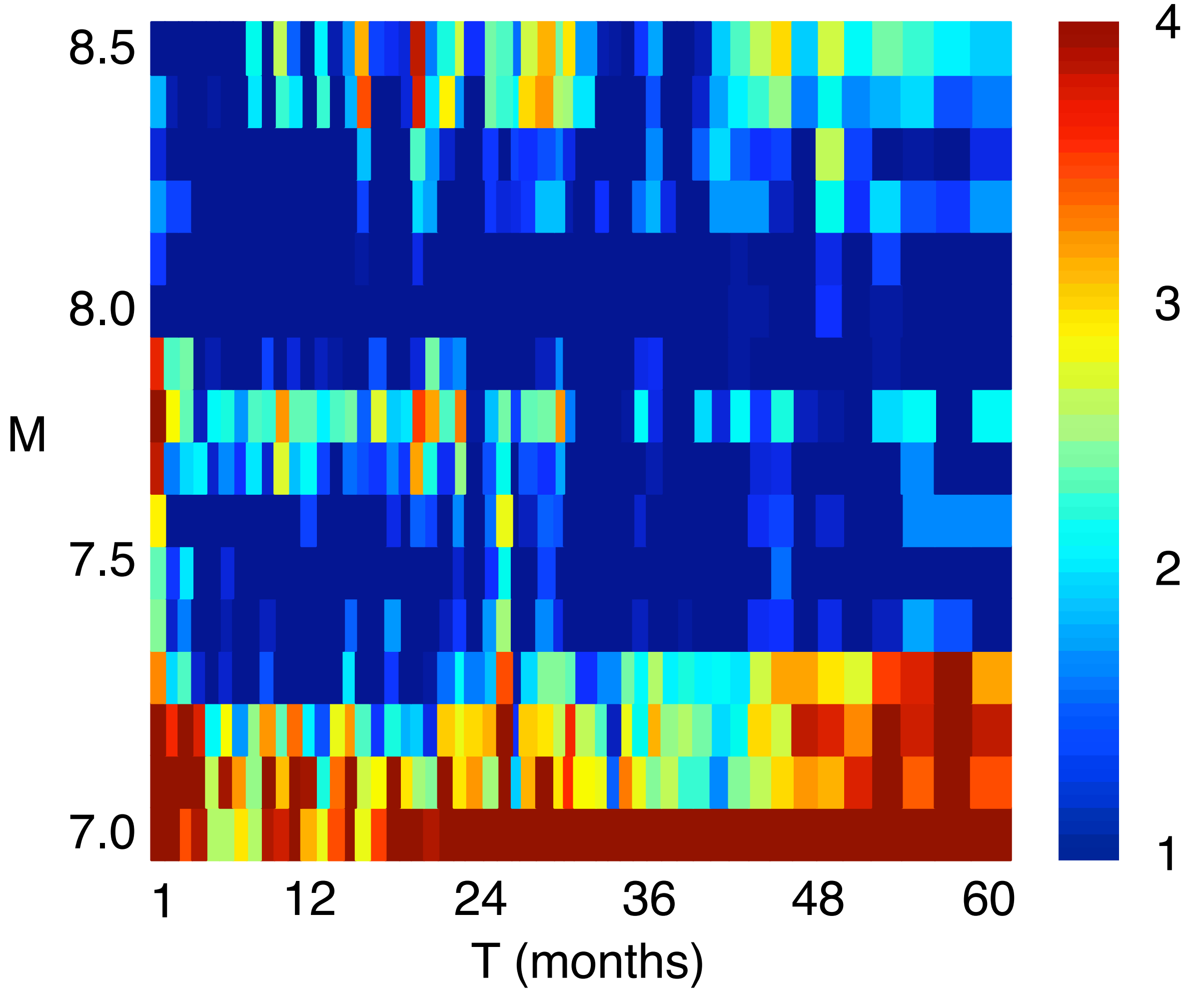
$$\sigma = \frac{V - \bar{V}}{\delta V}$$

- Use Gaussian distribution (Bell curve) to assess statistical significance

1	2	3	4
0.31	4.55E-02	2.7E-03	6.33E-05

Synthetic Catalogs

$$\sigma = \frac{V - \bar{V}}{\delta V}$$



Red= Statistically significant

σ ___

Blue= Statistically insignificant

Overpopulation significant only for M<7.3, regardless of T

Why is T<24 statistically significant?

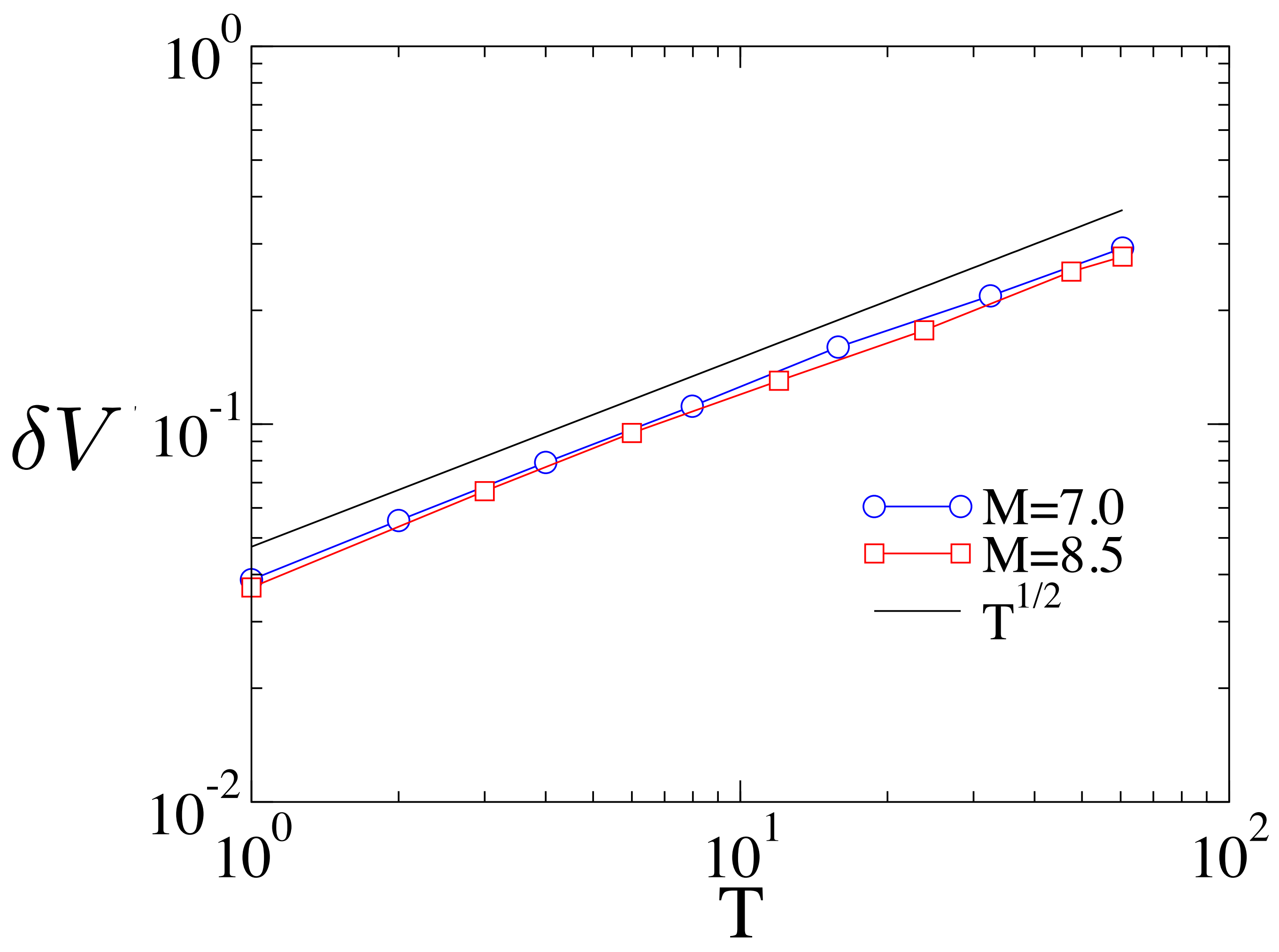
Variation with Time window

- Larger time intervals give less independent measurements

$$N = \frac{\text{Number of years} \times 12}{T}$$

- Fewer independent measurements give larger variation

$$\delta V \sim \frac{1}{\sqrt{N}} \sim \sqrt{T}$$



- Variation in variance is universal!

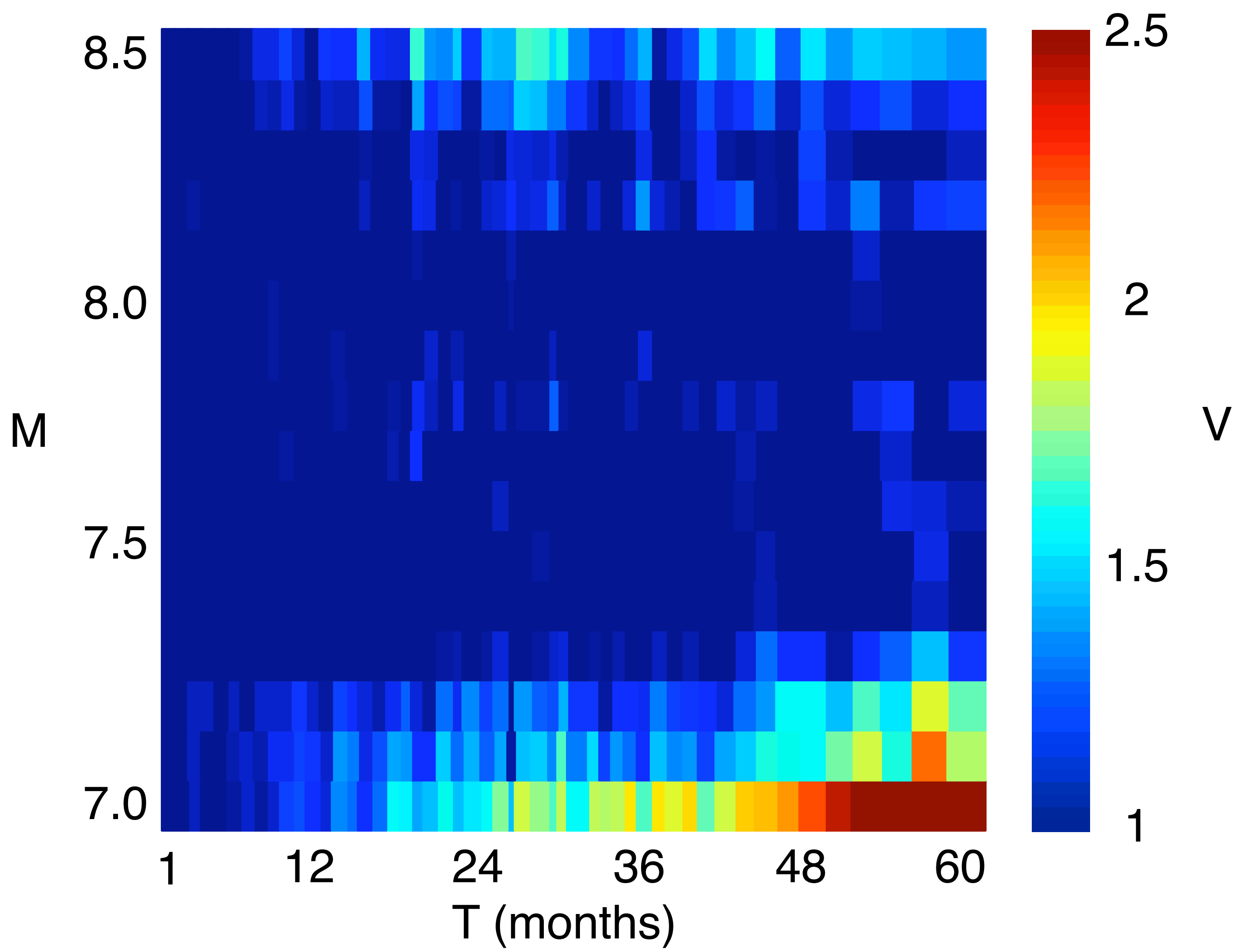
Small T analysis credible

Large T analysis questionable

Normalized variance: Aftershocks Removed

$$V = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle}$$

Random Distribution $V \approx 1$
Overpopulated Tail $V \gg 1$



Red= Overpopulated Tail

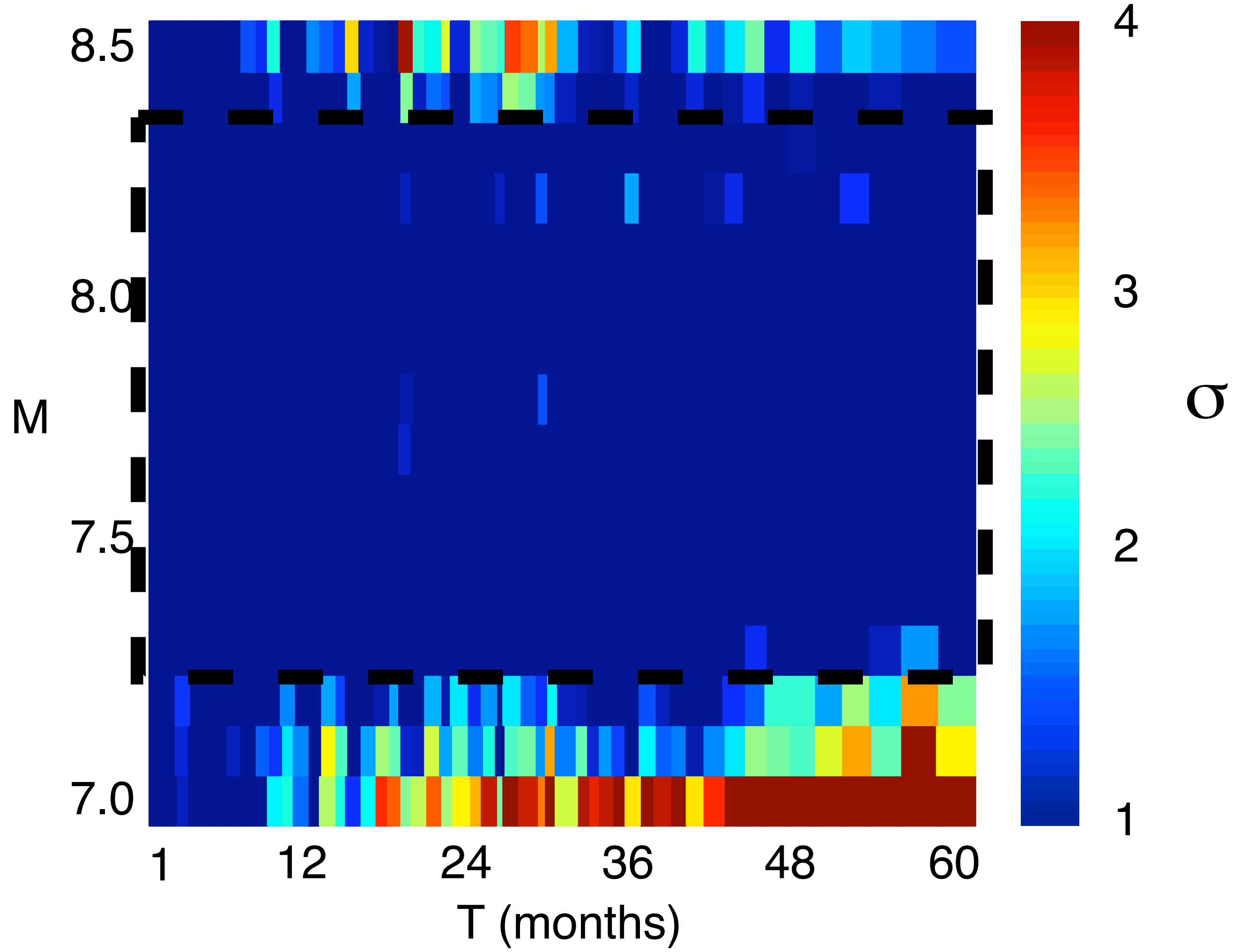
Blue= Random Distribution

Overpopulation for M<7.3, T>24

Is this overpopulation Statistically Significant?

Synthetic Catalogs: Aftershocks Removed

$$\sigma = \frac{V - \bar{V}}{\delta V}$$



Red= Statistically significant

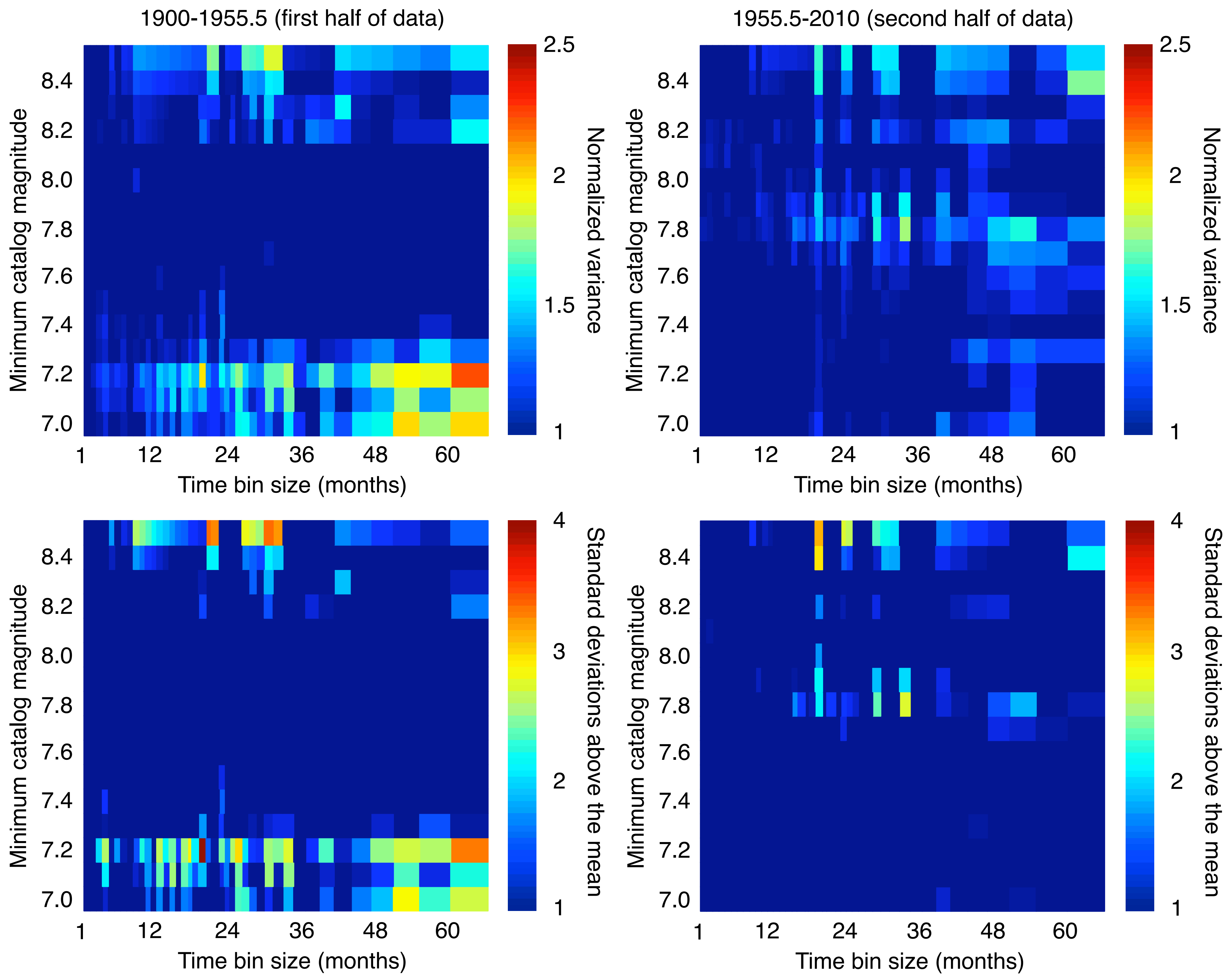
Blue= Statistically insignificant

Overpopulation significant only for M<7.2, T.24

Noise at M>8.3, <u>very few data points</u>

Let's compare 1900-1955 with 1955-2011

Mainshocks only



Stronger evidence: separately, each catalog is random

Issues

- Discrepancy between earlier and current data
- Discrepancy between databases
- Decluster: identify and remove aftershocks
- Very small of very large events