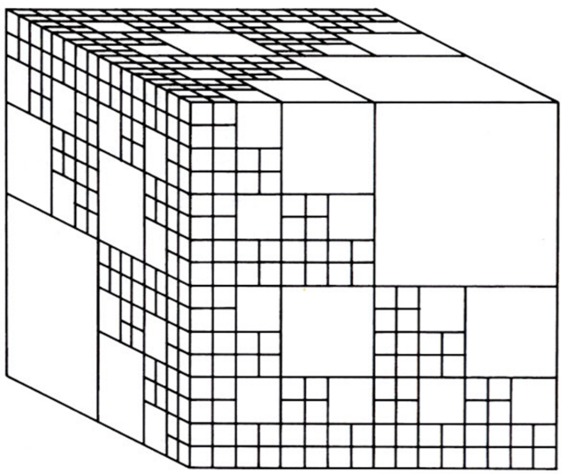
Insights on non-universal seismicity patterns from data and models

Yehuda Ben-Zion and Ilia Zaliapin

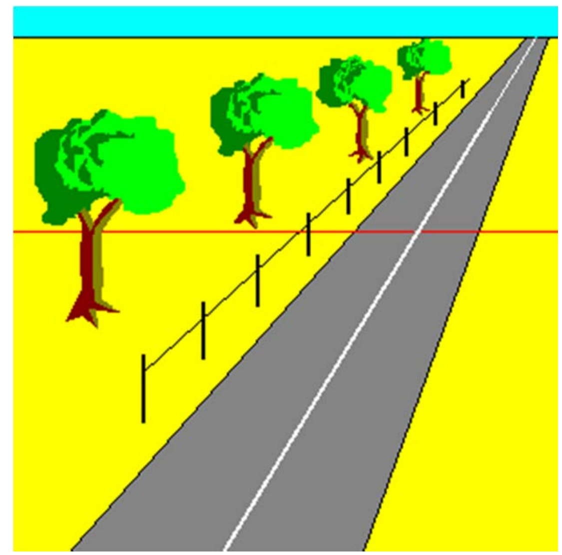
Fractal earthquakes and faults (**power laws**)



Mandelbrot (67), Kagan (82), King (83), Turcotte (86), Bak et al. (87)

Simple end-member cases with a single dynamic regime

Planar fault in homogeneous elastic solid (**limit cycles**)



Reid (1910), Anderson (1951), Maruyama (1963), Rice (1980)

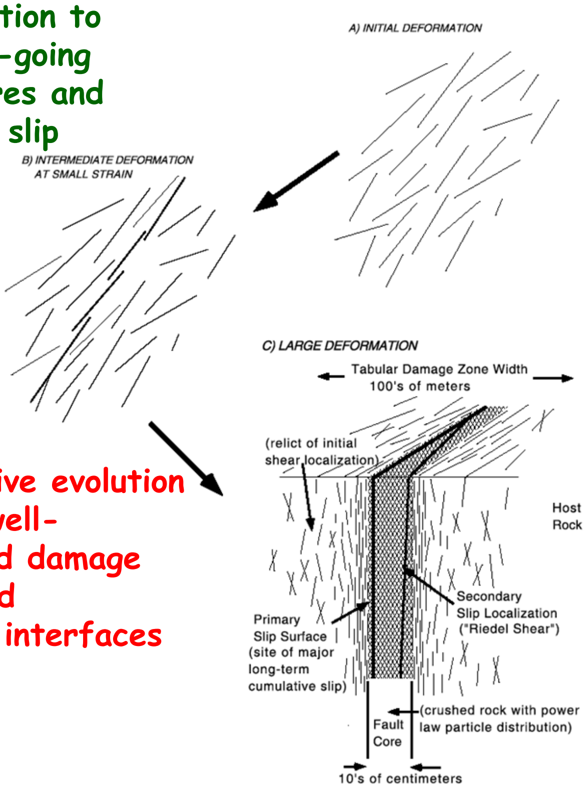
Evolutionary processes: greater dynamic richness (and complexity), including the above end-member cases and additional regimes in between!

Using data from large space-time domains can lead to loss of information and apparent scale-invariance from averaging. Using proper "selection criteria" may provide important region-specific information.

Phenomenology of earthquakes and faults

Evolution of Fault Zone Structures
(Ben-Zion and Sammis, 2003)

Localization to through-going structures and primary slip zones



Creation of granularity and band-limited fractal structures at several hierarchies.

Progressive evolution toward well-developed damage zones and material interfaces

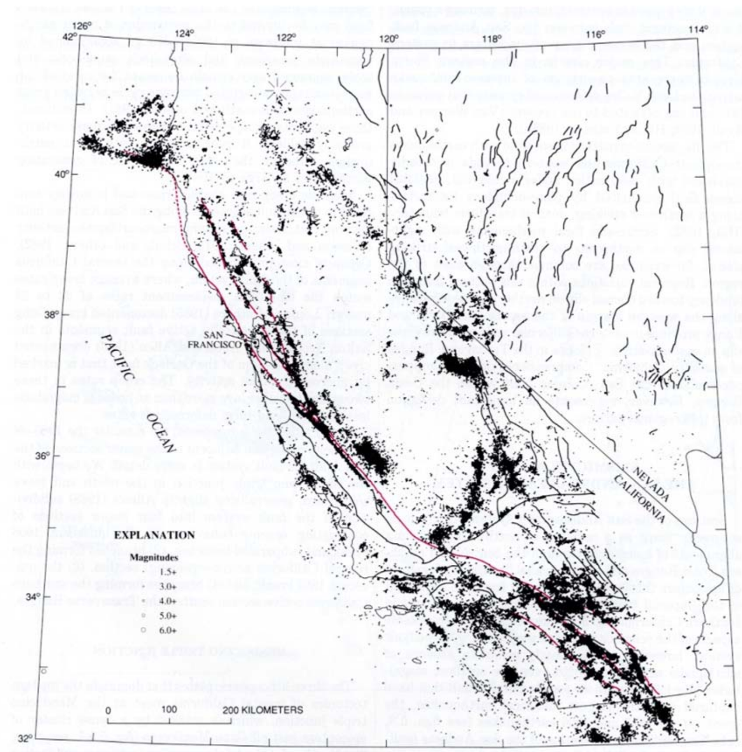
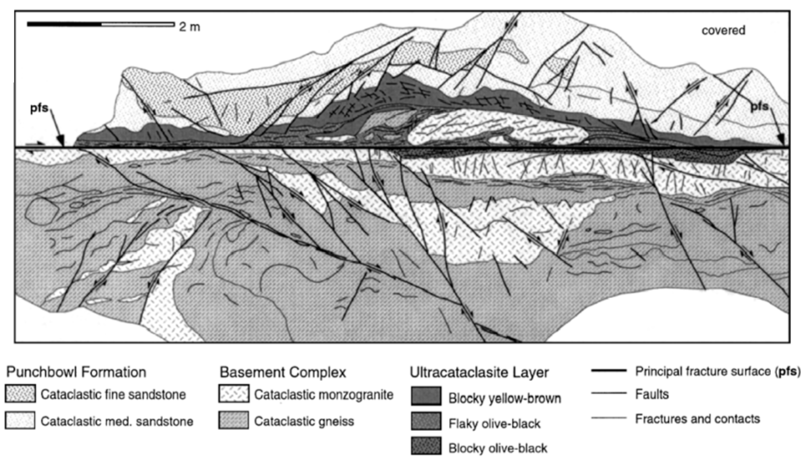


FIGURE 5.4.—Locations of 64,000 $M \geq 1.5$ earthquakes in California and western Nevada during 1980–86 and mapped Holocene faults (dotted where concealed; major branches of the San Andreas fault system marked in red).

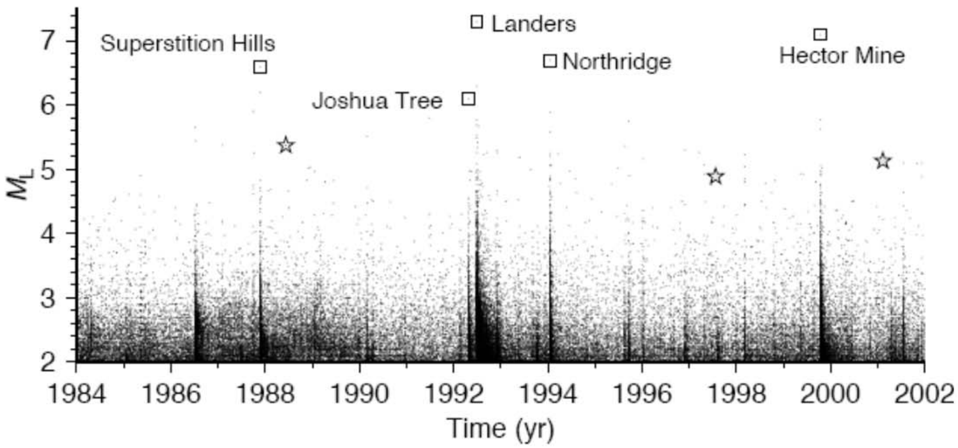
USGS (1990)

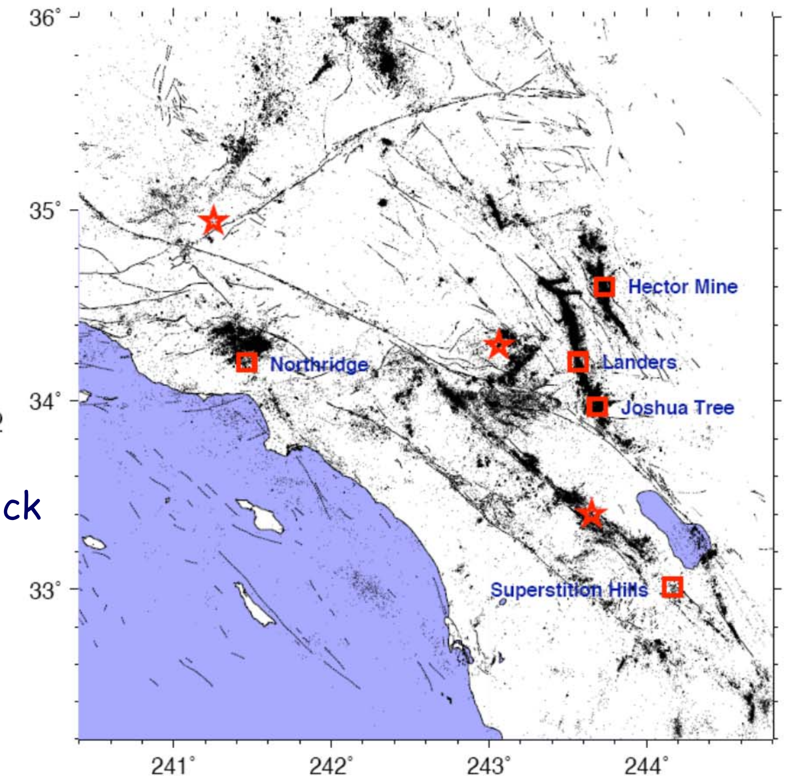
The Punchbowl fault: 44 km of slip (Chester and Chester, 1998)



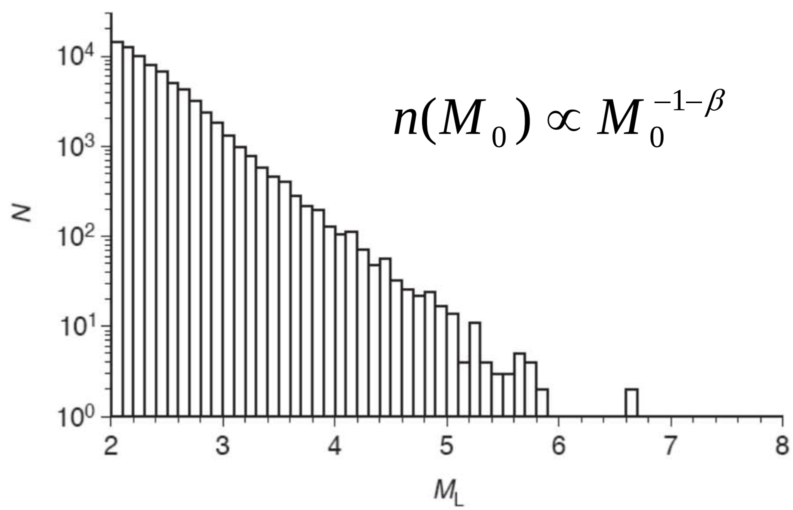
1984-2002 Southern California seismicity

Ben-Zion (2008) based on the seismicity catalog of Shearer et al. (2005)





Most, but not all, moderate events have clear aftershock sequences

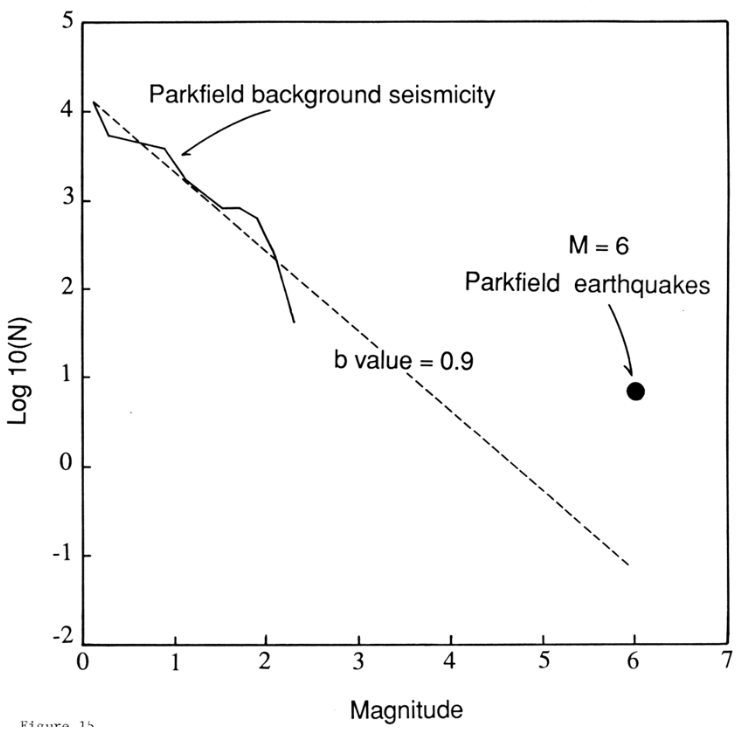


$$n(M_0) \propto M_0^{-1-\beta}$$

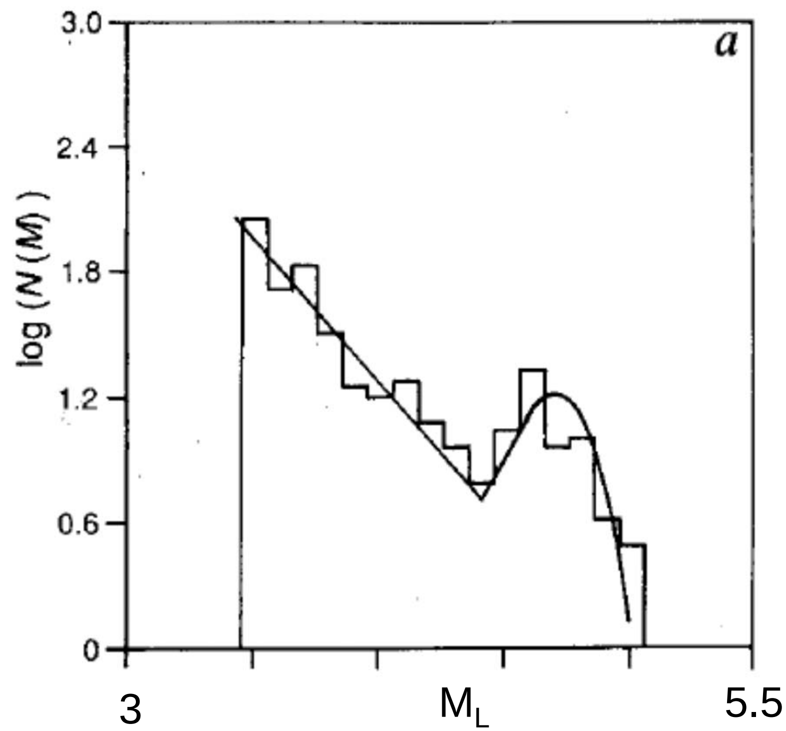
Power law frequency-size statistics (other than perhaps the largest events)

But statistics for relatively homogenous fault systems exhibit peaks at particular scales and are referred to as the "characteristic distribution".

The end of power law regime of small events and peak contain information on properties of the system.



Discrete statistics for seismicity along the Parkfield section of the SAF (Ben-Zion and Rice, 1993)



Discrete statistics for seismicity preceding the 1980 eruption of Mount St Helens (Main, 1992)

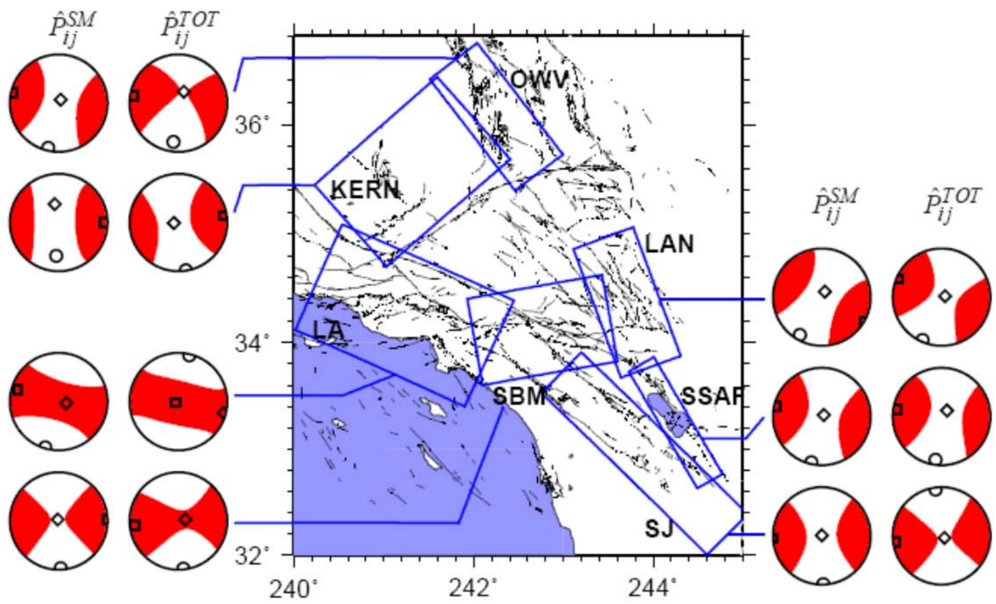
In general, regional statistics tend to be dominated by power laws and temporal clustering (in part due to averaging), while statistics of large individual faults tend to include characteristic space-time scales (within overall complex behavior).

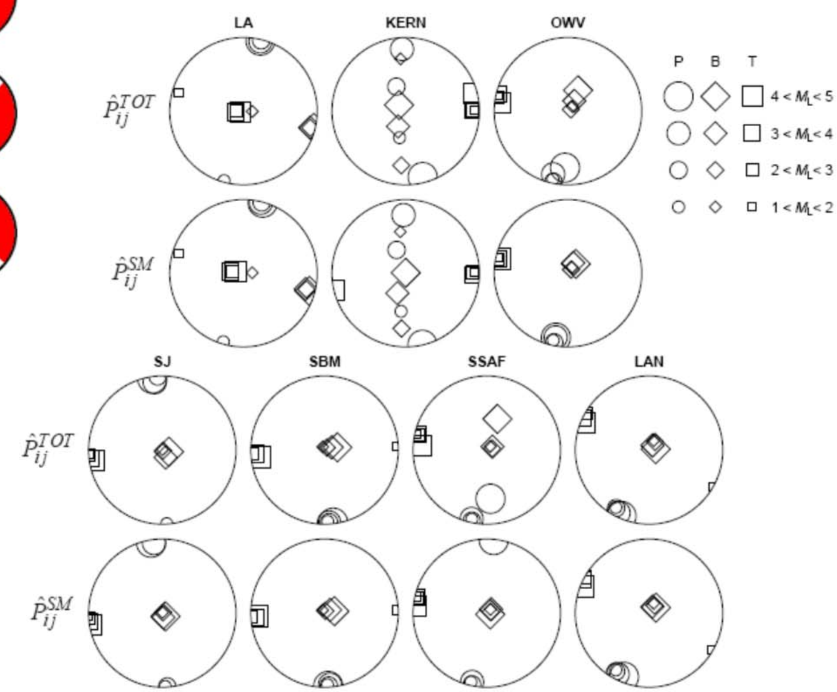
In some cases more complex "mode-switching" behavior may exist.

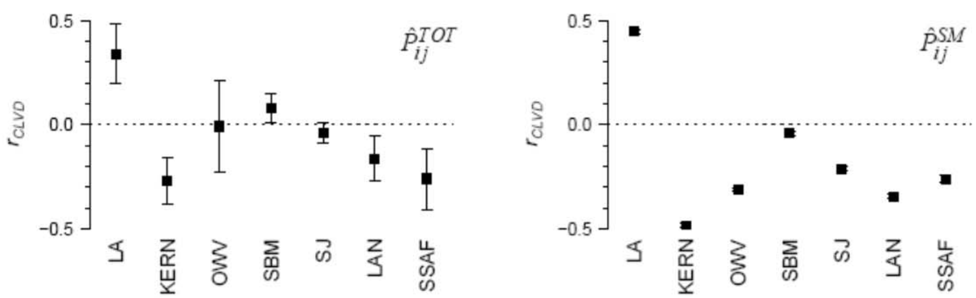
Potency tensor summations for 170,000 *SC* earthquakes with 0 < M_L < 5

(Bailey, Ben-Zion, Becker, Holschneider 2008, 2009)

Beachballs show orientations of compression (white) and extension (red)







Size of the CLVD component for each summation type and region

Potency tensor summations for each region and each magnitude range

Detailed observations show clear persistent diversity rather than a single type of behavior.

Improved understanding requires analysis of evolutionary processes and different dynamic regimes.

Key Questions:

- How are geometrical, mechanical, and rheological properties of fault zones and their surrounding media related to different types of earthquake patterns in space-time-energy domains (e.g., localized vs. distributed spatial structures, power-law vs. characteristic frequency-size (FS) statistics, quasi-periodic vs. clustered temporal behavior, Omori-Utsu aftershock sequences vs. swarm-type response).

- Are there connections between different types of earthquake patterns considered usually in isolation (e.g., are the forms of FS and temporal statistics related, and if yes how)?

- When and how can we extrapolate results of low magnitude seismicity to large earthquake behavior?

- On what time scale is the seismic response to tectonic loading stationary, if at all?

- How are foreshock-mainshock-aftershock properties related to the "brittleness" of a given area and the regional seismic potential?

Earthquake clusters in southern California: Identification and relation to physical properties of the crust

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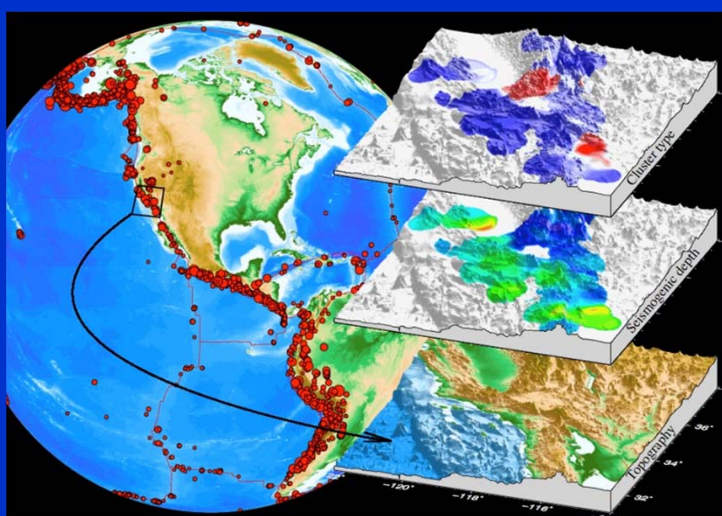


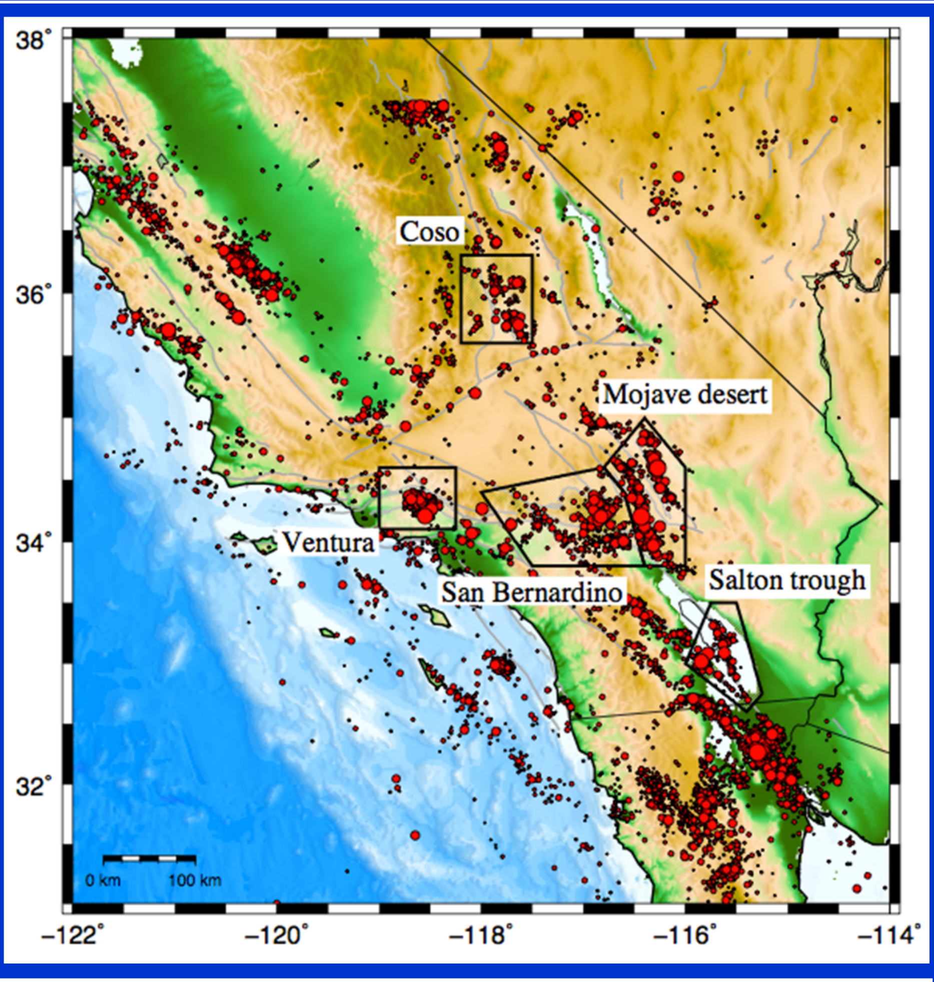
Baiesi and Paczuski, *PRE*, **69**, 066106 (2004)
Zaliapin *et al.*, *PRL*, **101**, 018501 (2008)
Zaliapin and Ben-Zion, *GJI*, **185,** 1288–1304 (2011)
Zaliapin and Ben-Zion, *JGR*, **118,** 2847-2864 (2013a)
Zaliapin and Ben-Zion, *JGR*, **118,** 2865-2877 (2013b)

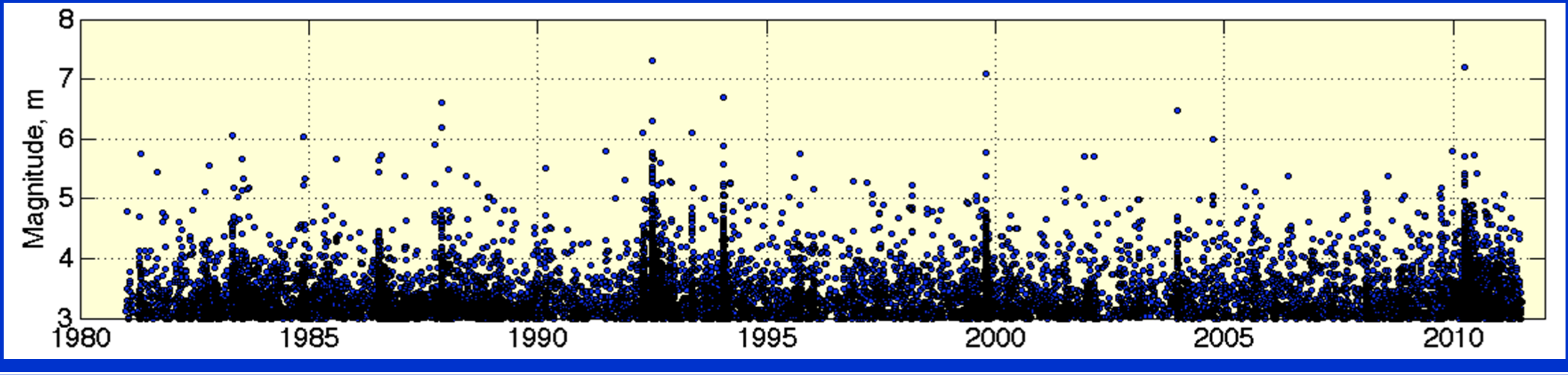
Data

- Southern California catalog: Hauksson, Yang, Shearer (2012) available from SCEC data center; 111,981 earthquakes with $m \geq 2$

- Five special study regions

- Heat flow data from www.smu.edu/geothermal





Distance from an earthquake j to an earlier earthquake i :

Definition:

(Fractal) dimension of events

$$\eta \propto \tau r^{d} 10^{-bm_i}, \quad \tau > 0$$

Intercurrence time

Spatial distance

Gutenberg-Richter law

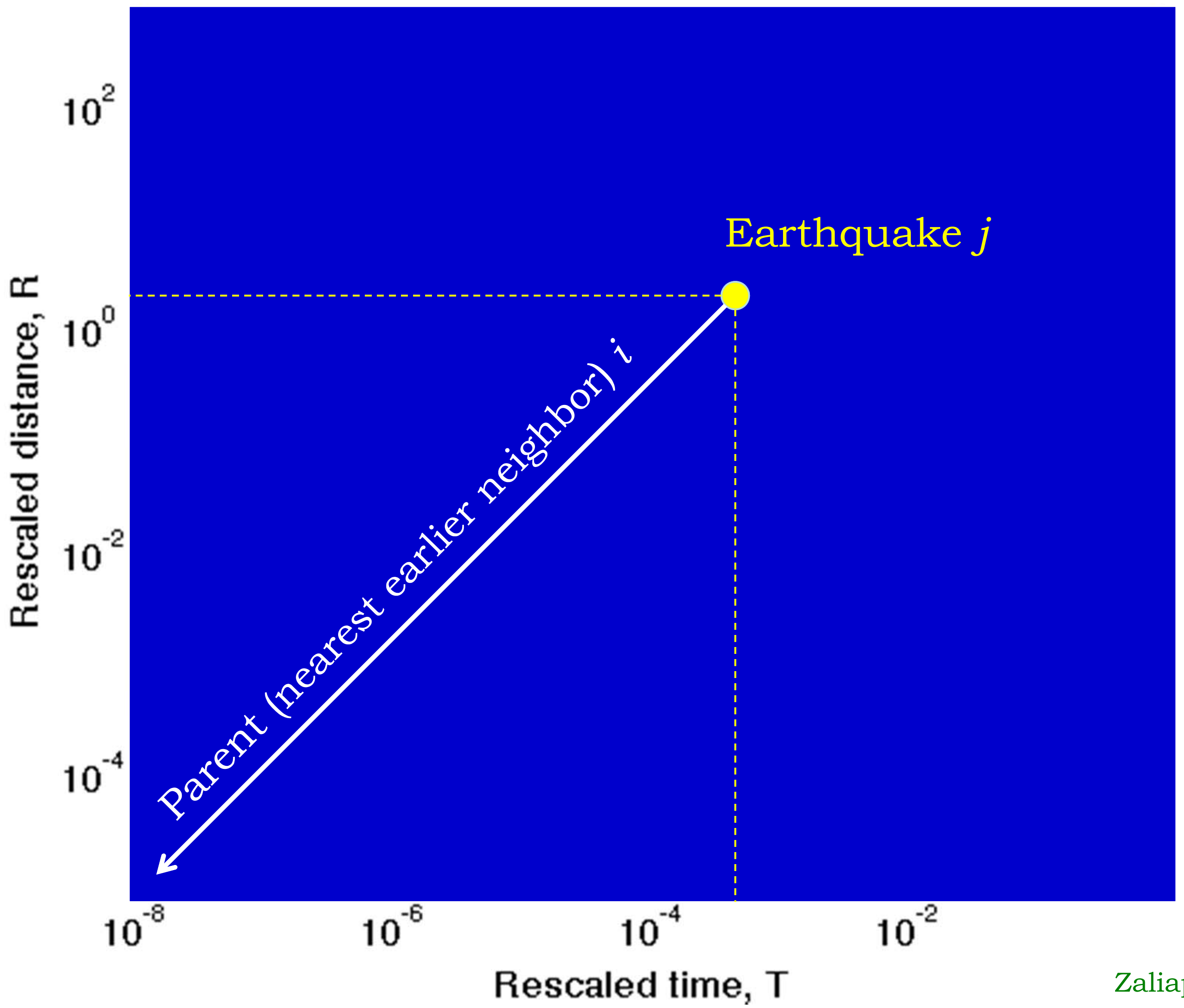
Property:

$$\eta = TR, \quad \log\eta = \log T + \log R$$

Rescaled time $T = \tau 10^{-bm_i/2}$, Rescaled distance $R = r^{d} 10^{-bm_i/2}$

[M. Baiesi and M. Paczuski, PRE, **69**, 066106 (2004)]
[Zaliapin *et al.*, *PRL*, **101**, 018501 (2008)]

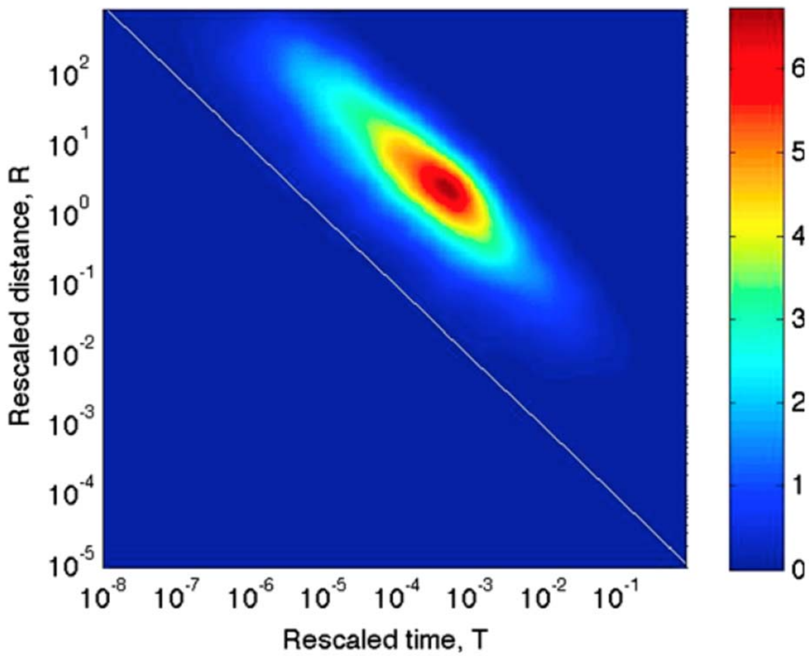
Assignment of parent events



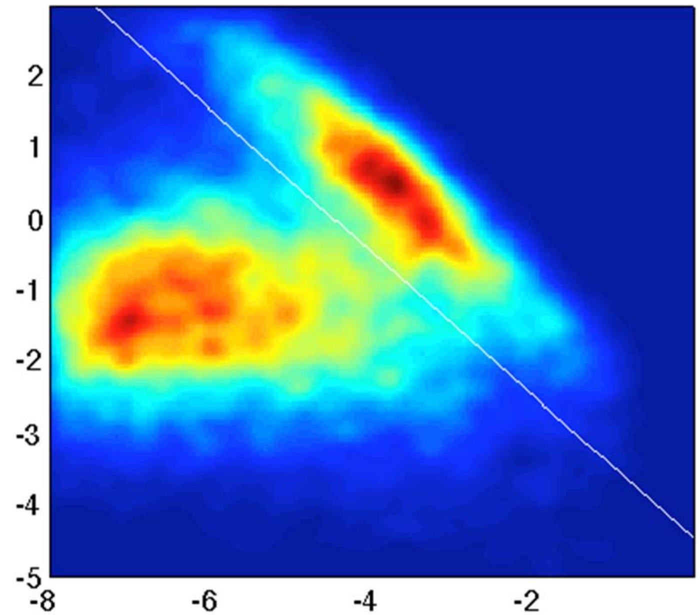
Zaliapin et al., *PRL* (2008)
Zaliapin and Ben-Zion, *JGR* (2013)

Background and clustered events in models

Homogeneous Poisson process



ETAS model



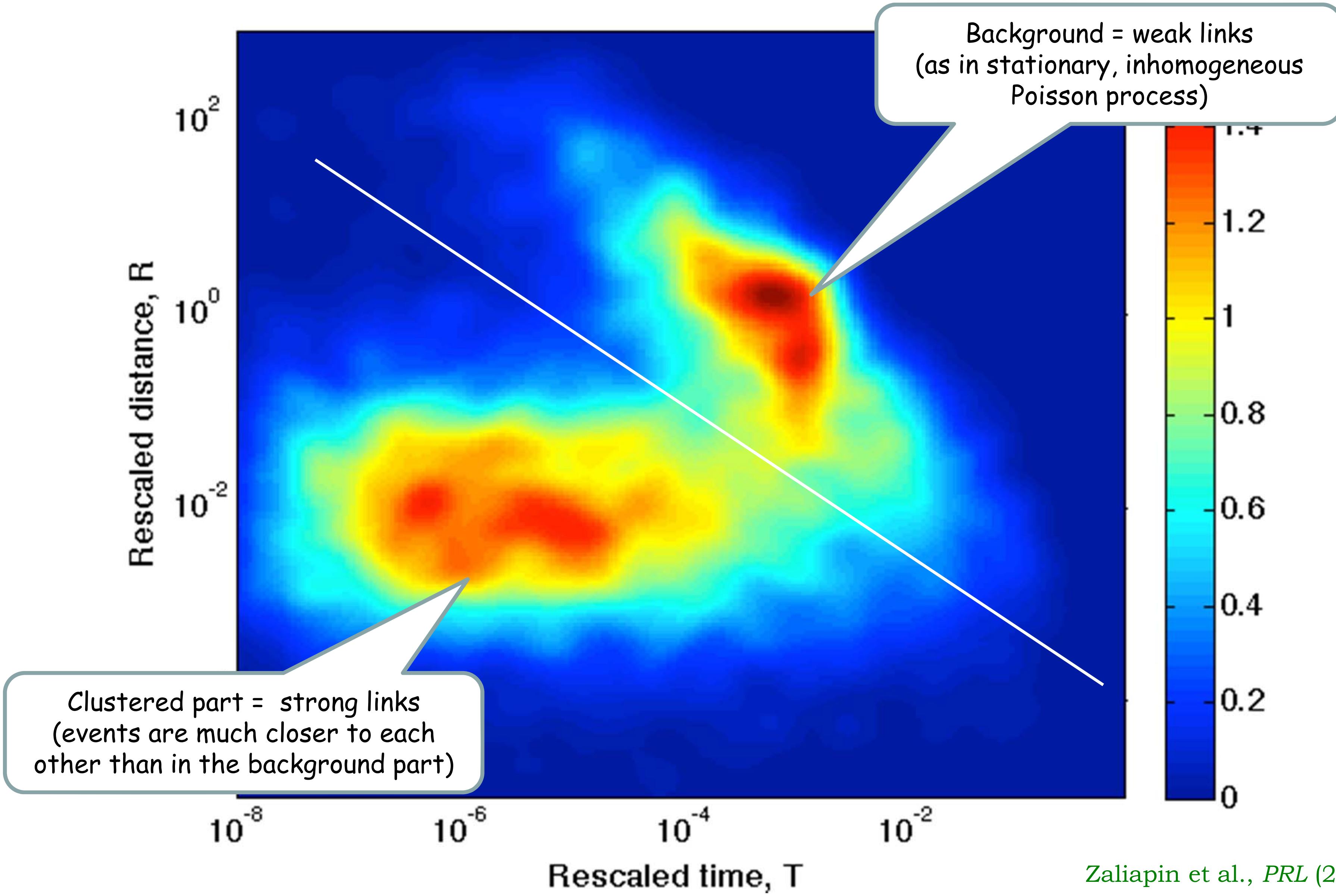
The **Epidemic-type Aftershock-sequences (ETAS)** model combines [e.g., Ogata, 1999] the modified Omori-Utsu law with the Gutenberg-Richter frequency-magnitude relation for a history-dependent occurrence rate of a point process in the form

$$\lambda(t \mid H_t) = \mu + \sum_{t_i < t} \frac{K_0 \exp[\alpha(M_i - M_c)]}{(t - t_i + c)^p}$$

The ETAS model provides good generic results ("null hypothesis") to use when attempting to find additional features of seismicity.

However, the ETAS model does NOT provide a full description of seismicity.

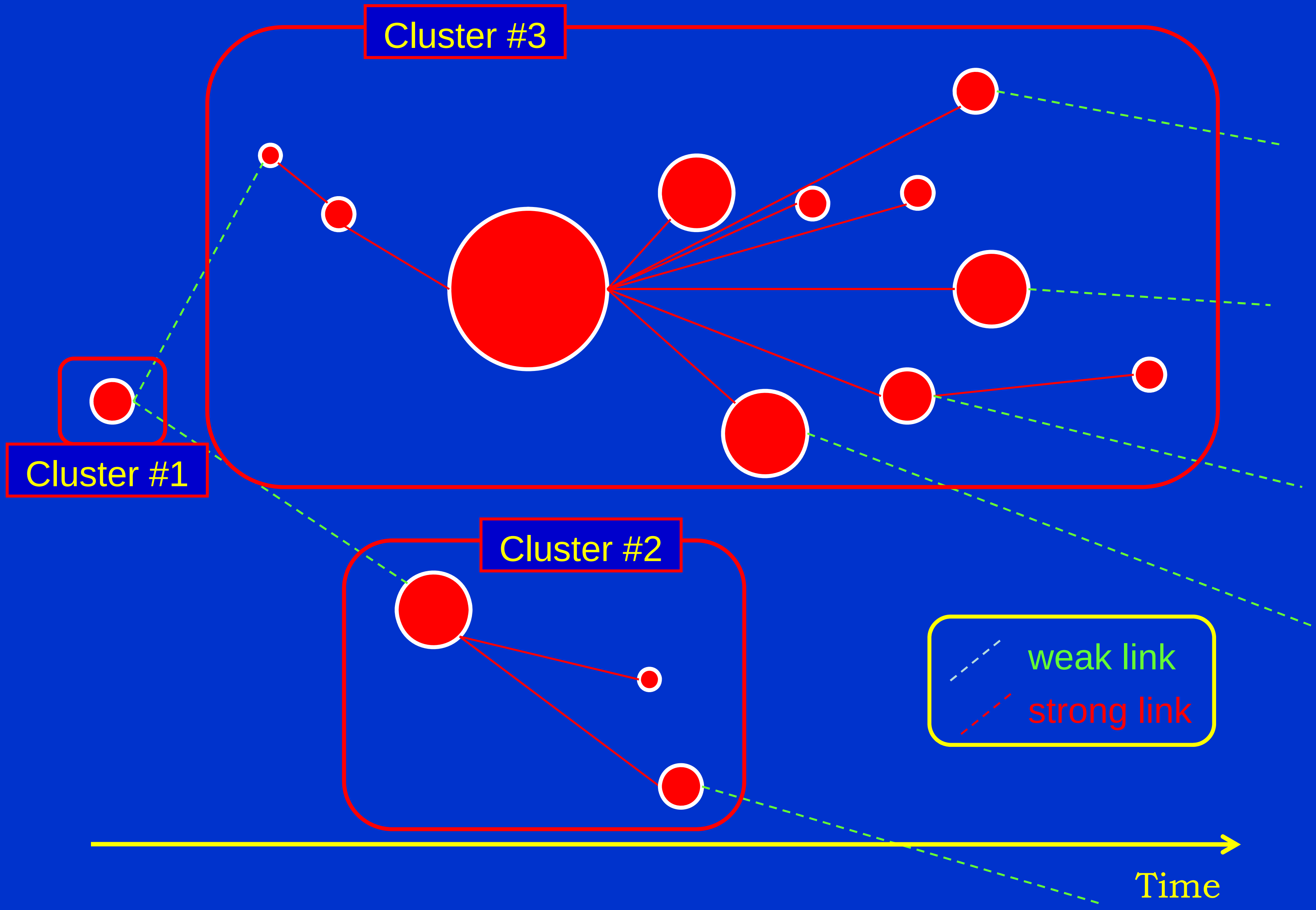
Separation of clustered and background events in southern California



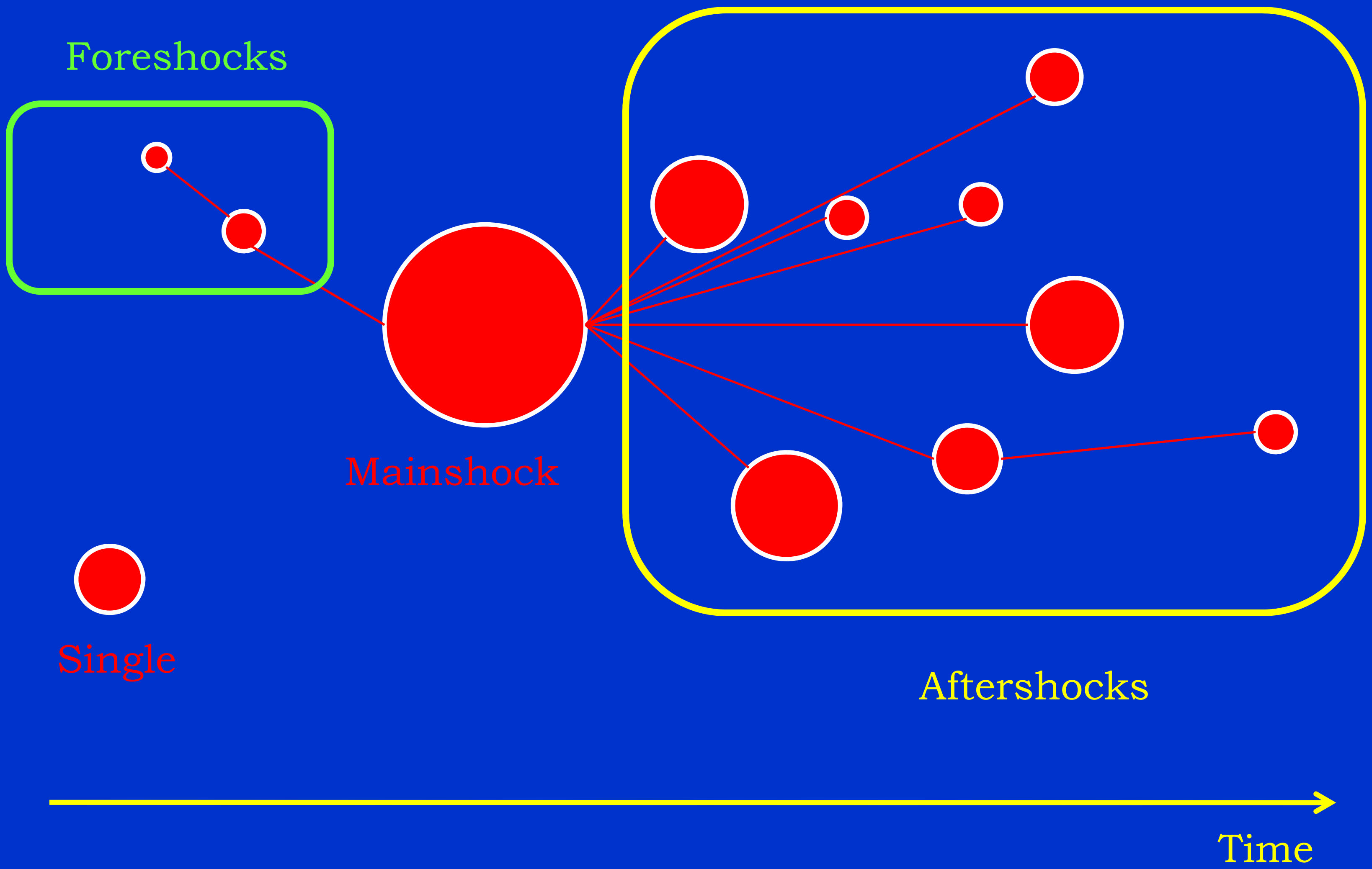
Zaliapin et al., *PRL* (2008)
Zaliapin and Ben-Zion, *JGR* (2013)

Seismicity as a flow of clusters

Identification of clusters: data driven

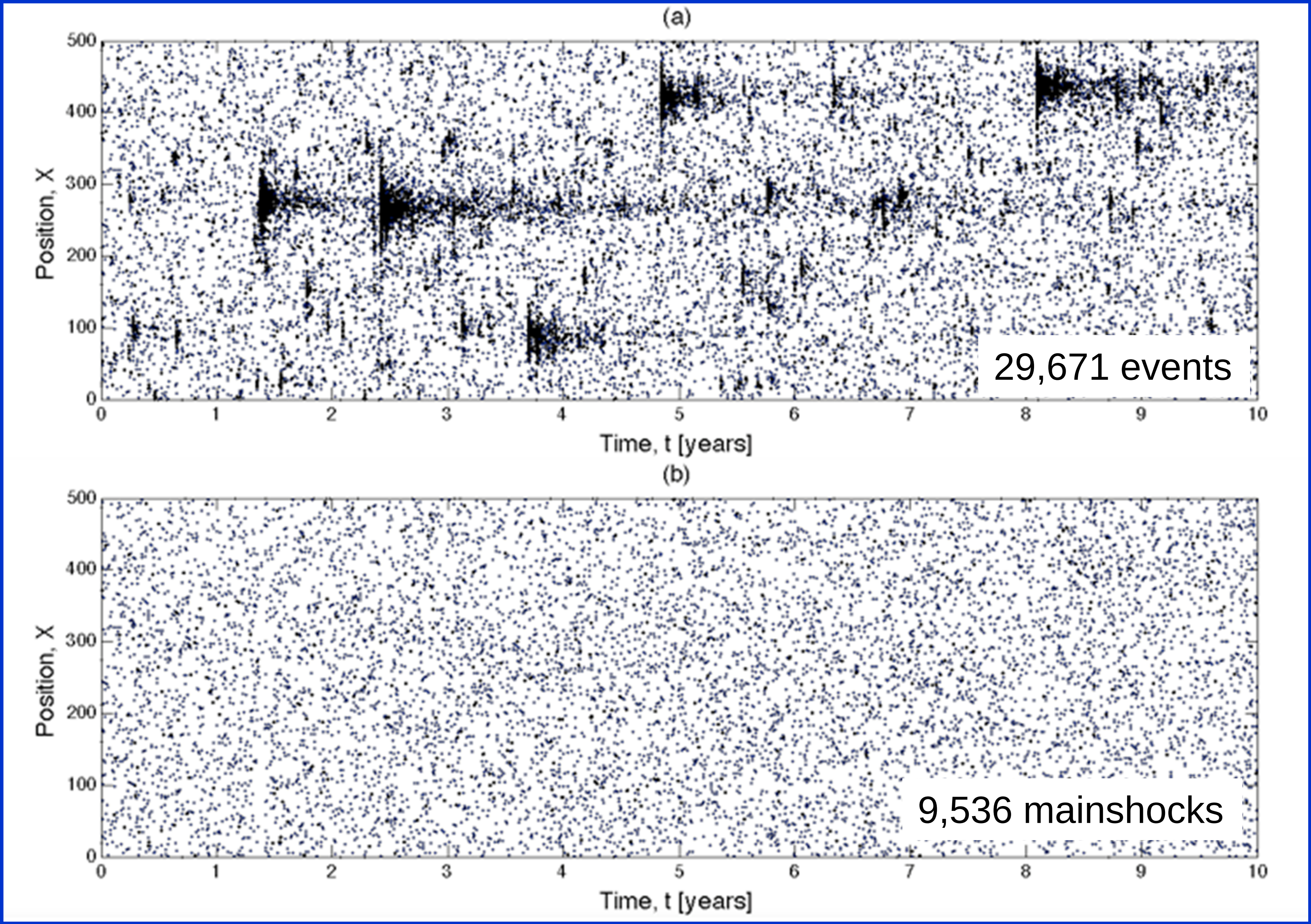


Identification of event types: problem driven

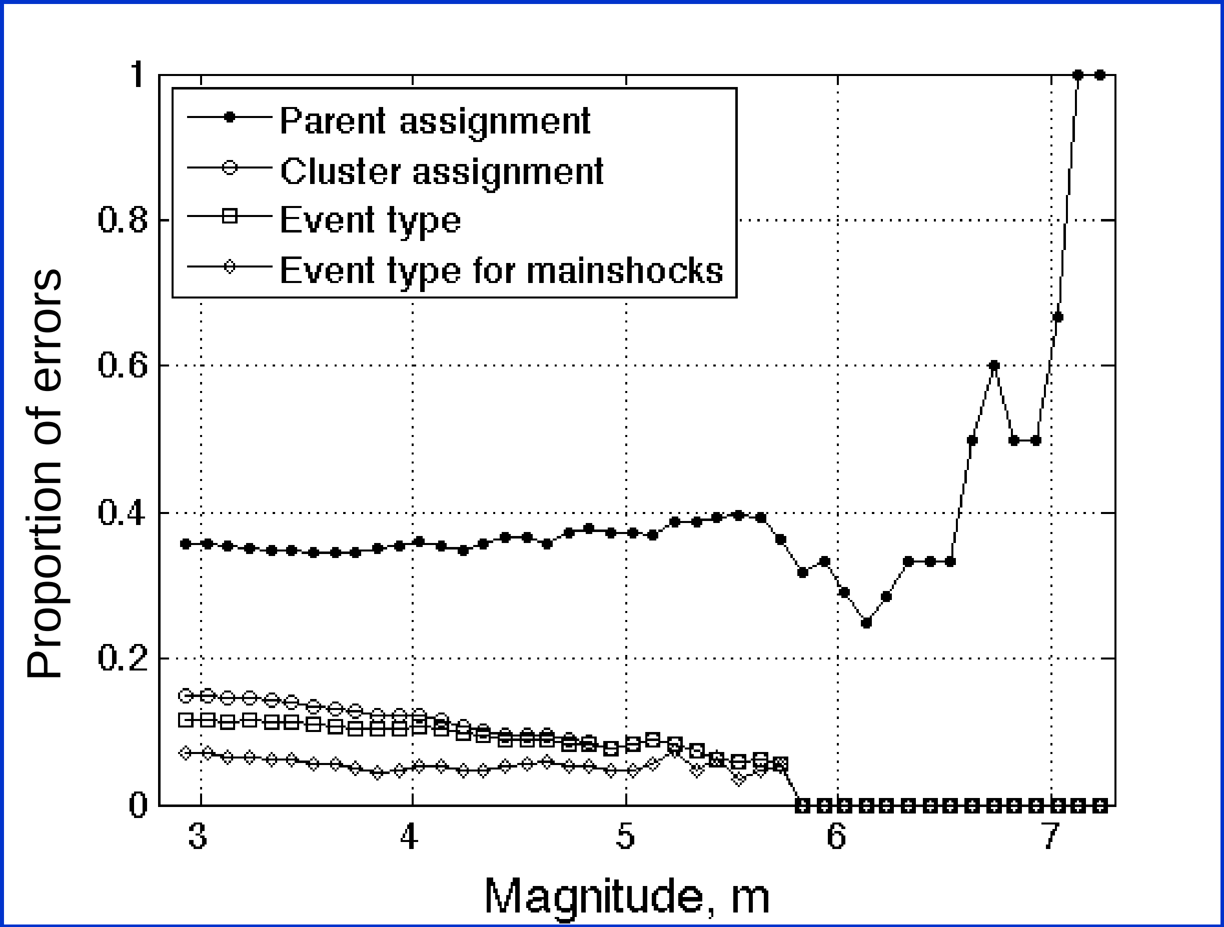


Quality and stability of cluster identification

ETAS declustering: Example



ETAS cluster analysis: Quality

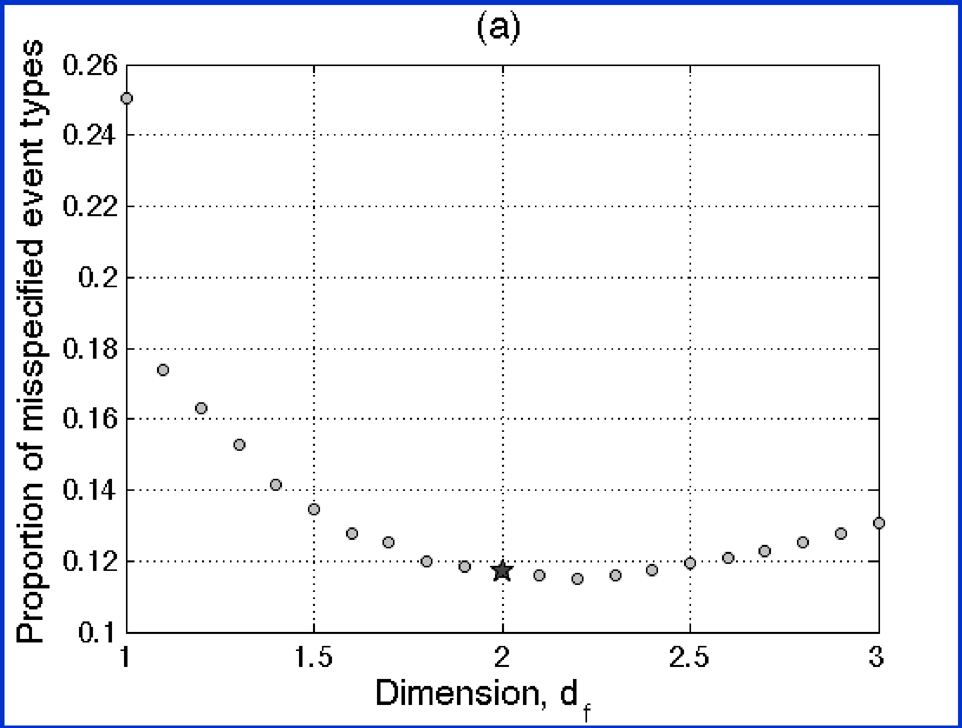


Zaliapin and Ben-Zion, *JGR* (2013)

ETAS cluster analysis: Stability

Stability with respect to:

- 3 numerical parameters of algorithm
- Catalog incompleteness
- Minimal reported magnitude
- Location error



Zaliapin and Ben-Zion, *JGR* (2013)

Main types of EQ clusters

① Burst-like clusters

- Represent brittle fracture. Large b-value (b=1), small number of events, small proportion of foreshocks, short duration, small area, isotropic spatial distribution.
- Tend to occur in regions with low heat flow, non-enhanced fluid content, relatively large depth => increased effective viscosity.

② Swarm-like clusters

- Represent brittle-ductile fracture. Small b-value (b=0.6), large number of events, large proportion of foreshocks, long duration, large area, anisotropic channel-like spatial pattern.
- Tend to occur in regions with high heat flow, increased fluid content, relatively shallow depth => decreased effective viscosity.

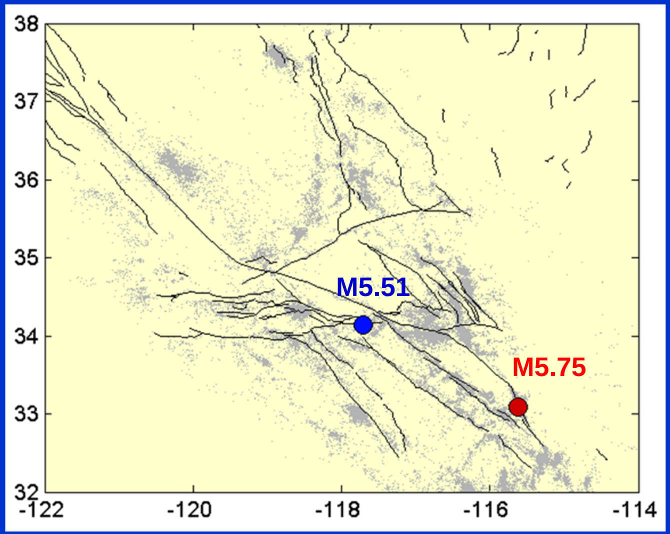
③ Singles

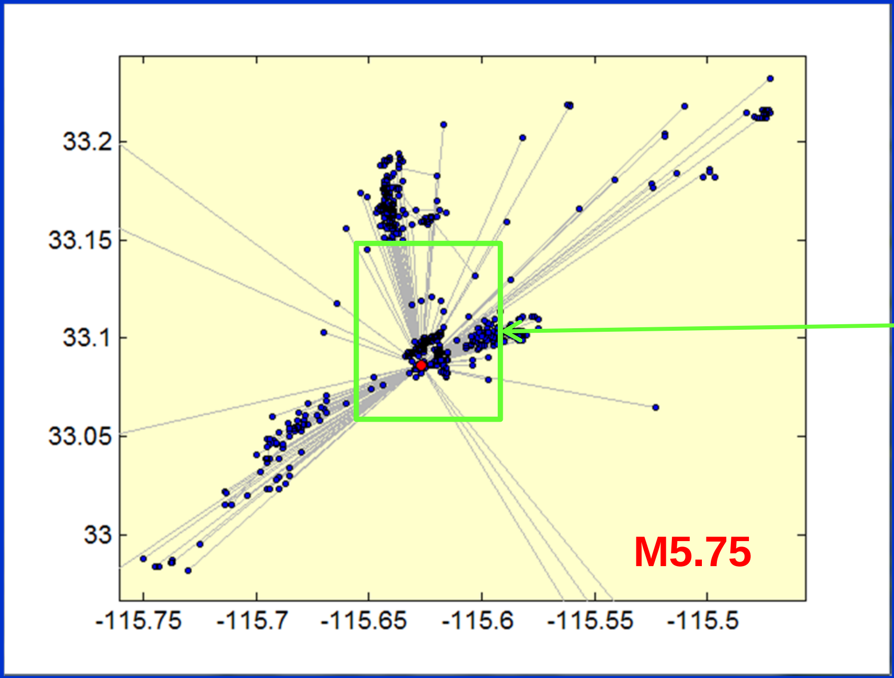
- Highly numerous in all regions; some but not all are related to catalog resolution.

④ Clusters of the largest events

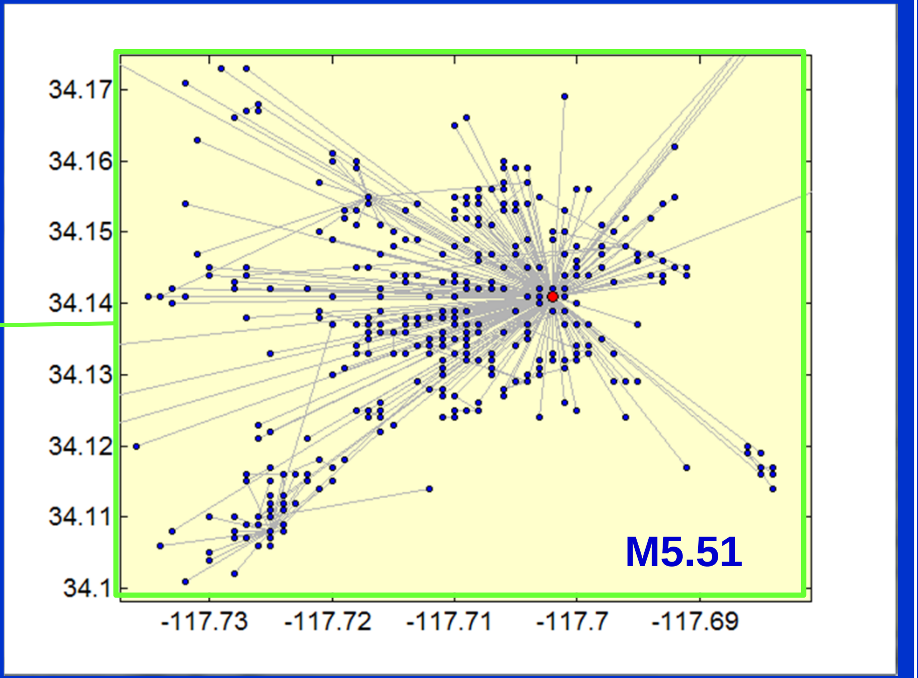
- Most prominent clusters; object of the standard cluster studies. Not representative of the majority of clusters (mixture of types 1-3).

Swarm vs. burst like clusters: Spatial distribution



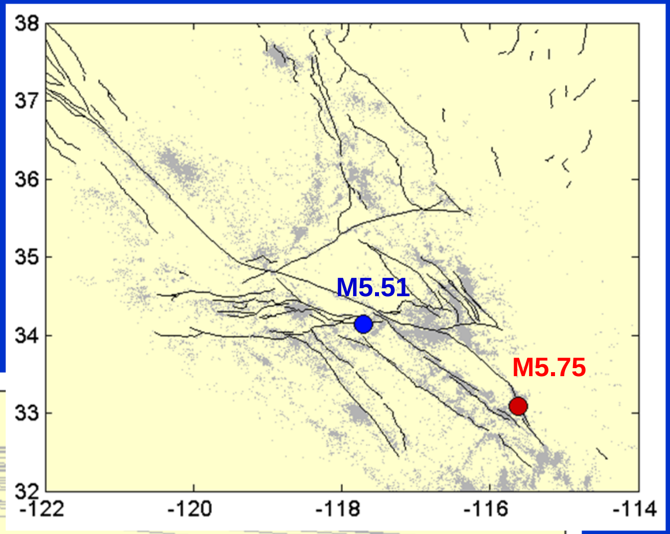


Swarm-like cluster

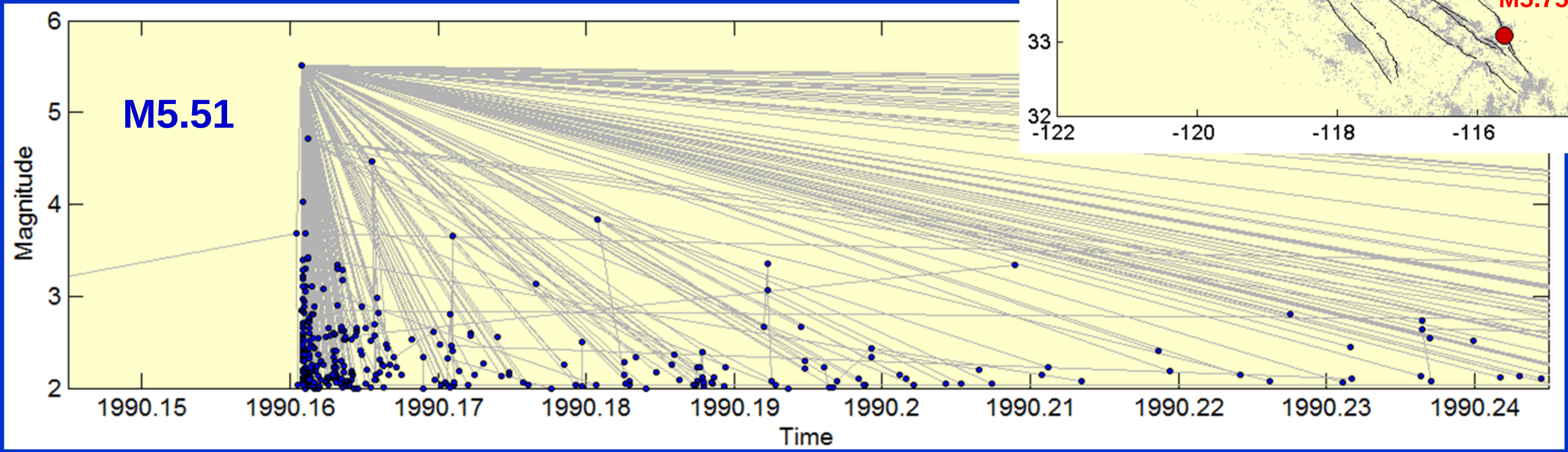


Burst-like cluster

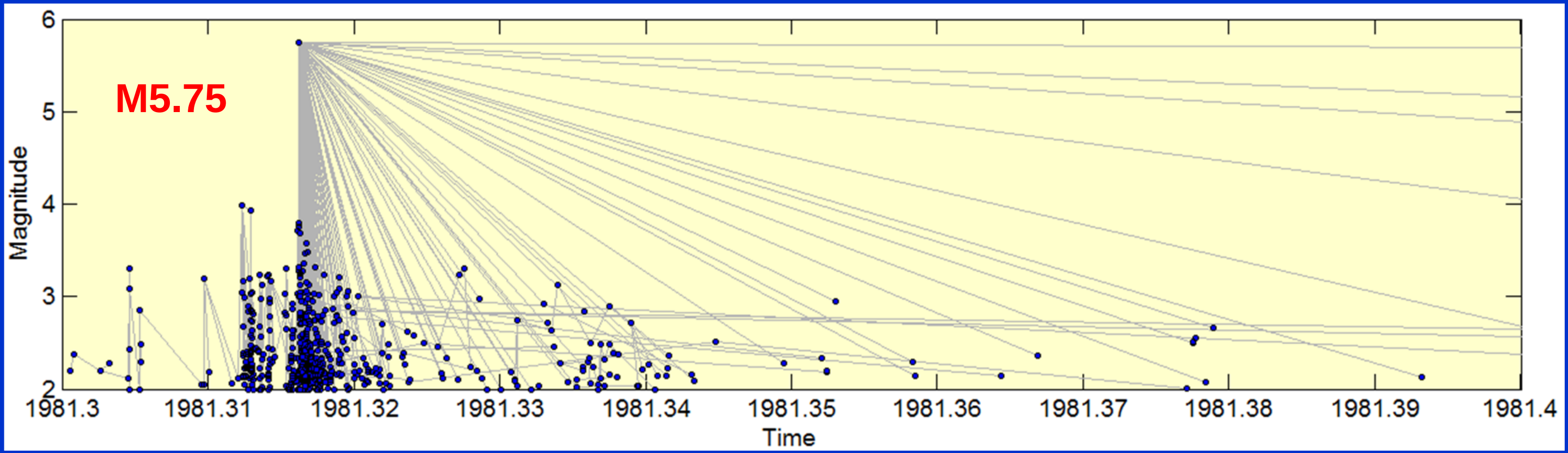
Swarm vs. burst like clusters: Foreshock productivity



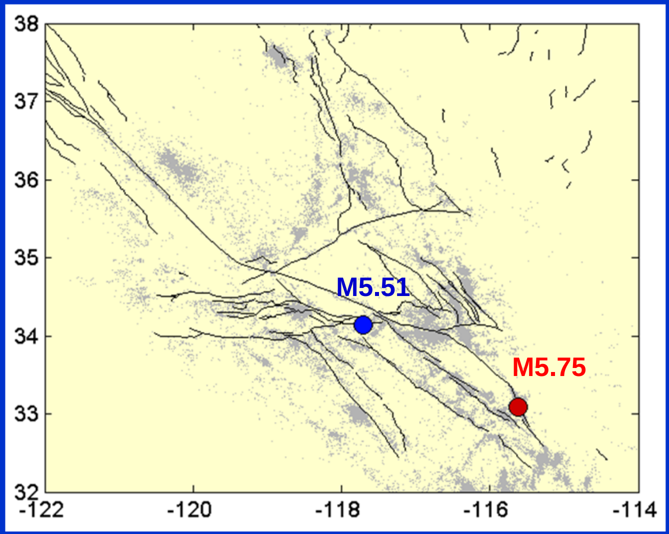
Burst-like

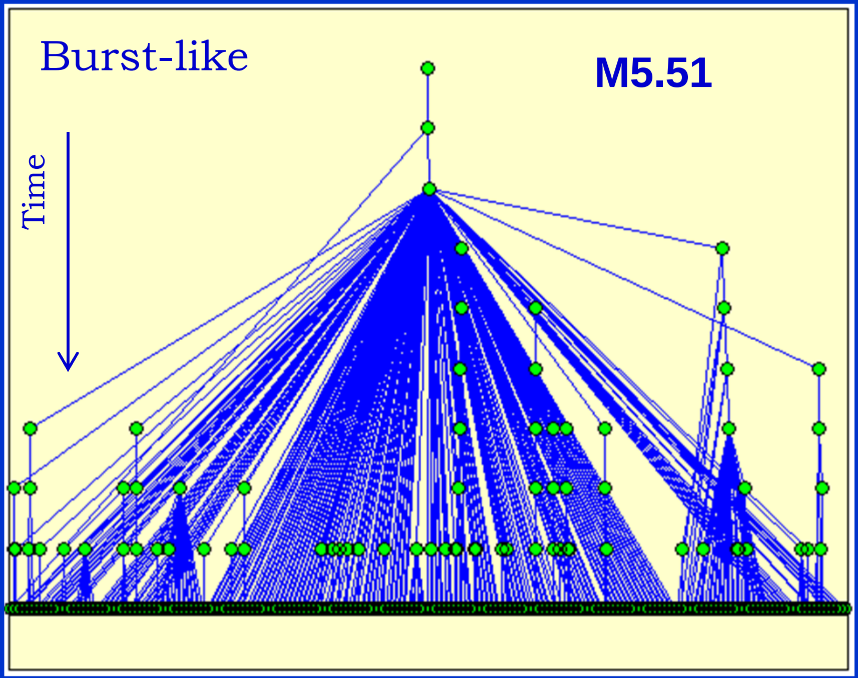


Swarm-like

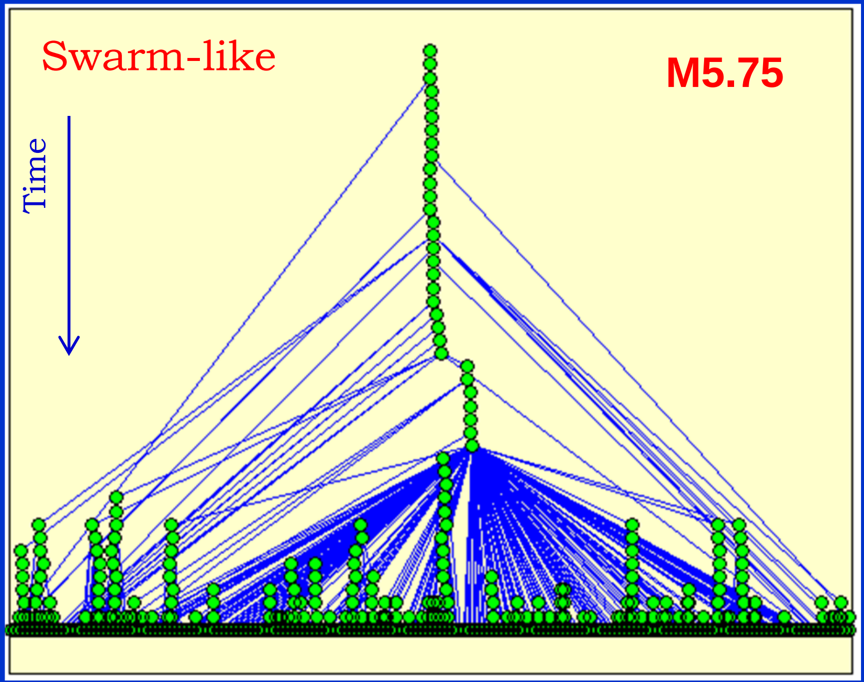


Swarm vs. burst like clusters: Topologic representation



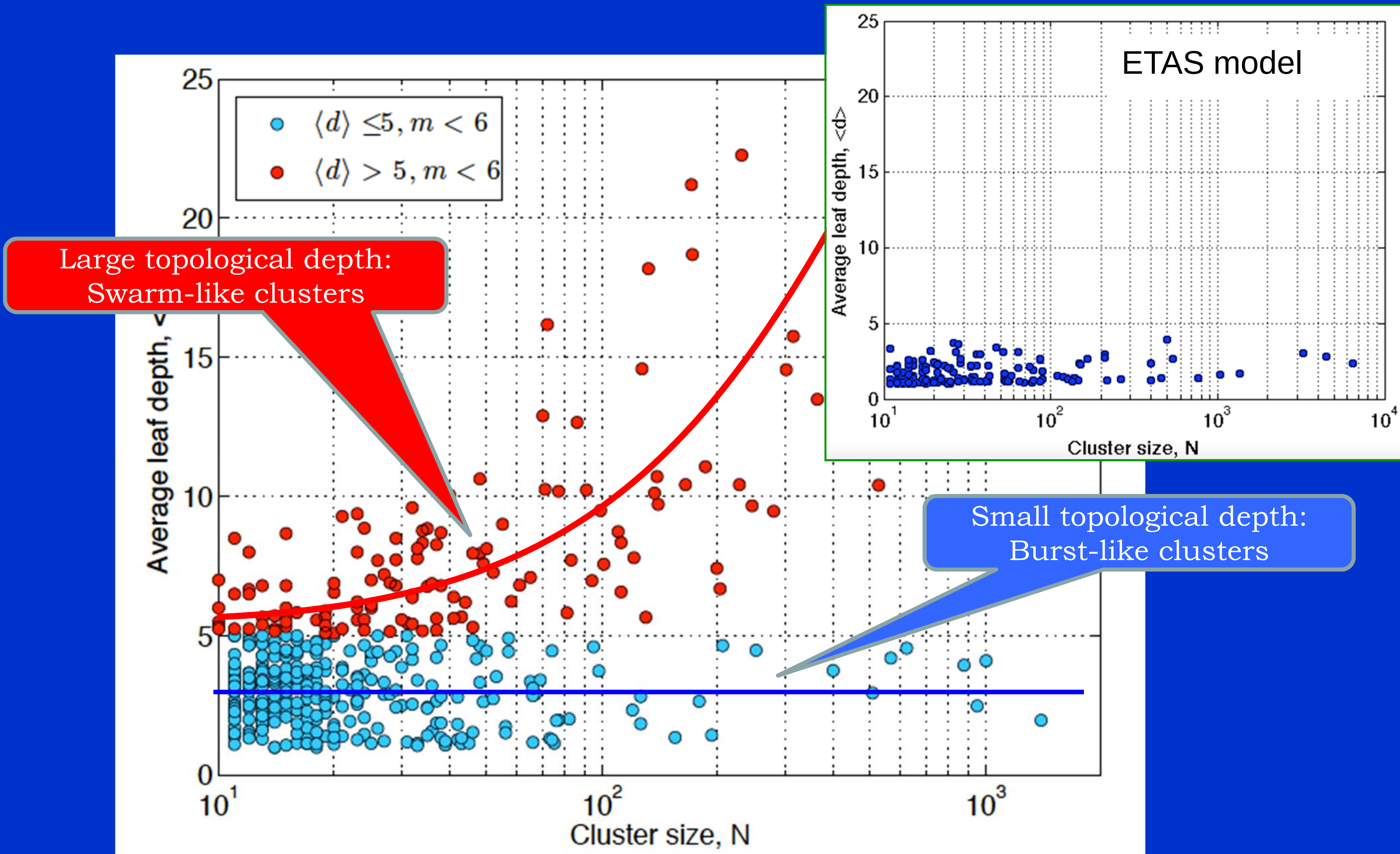


L= 417, tree depth = 9, ave. depth = 3.8



L= 572, tree depth = 44, ave. depth = 30.3

Average leaf depth (number of generations from a leaf to the root): Bimodal structure

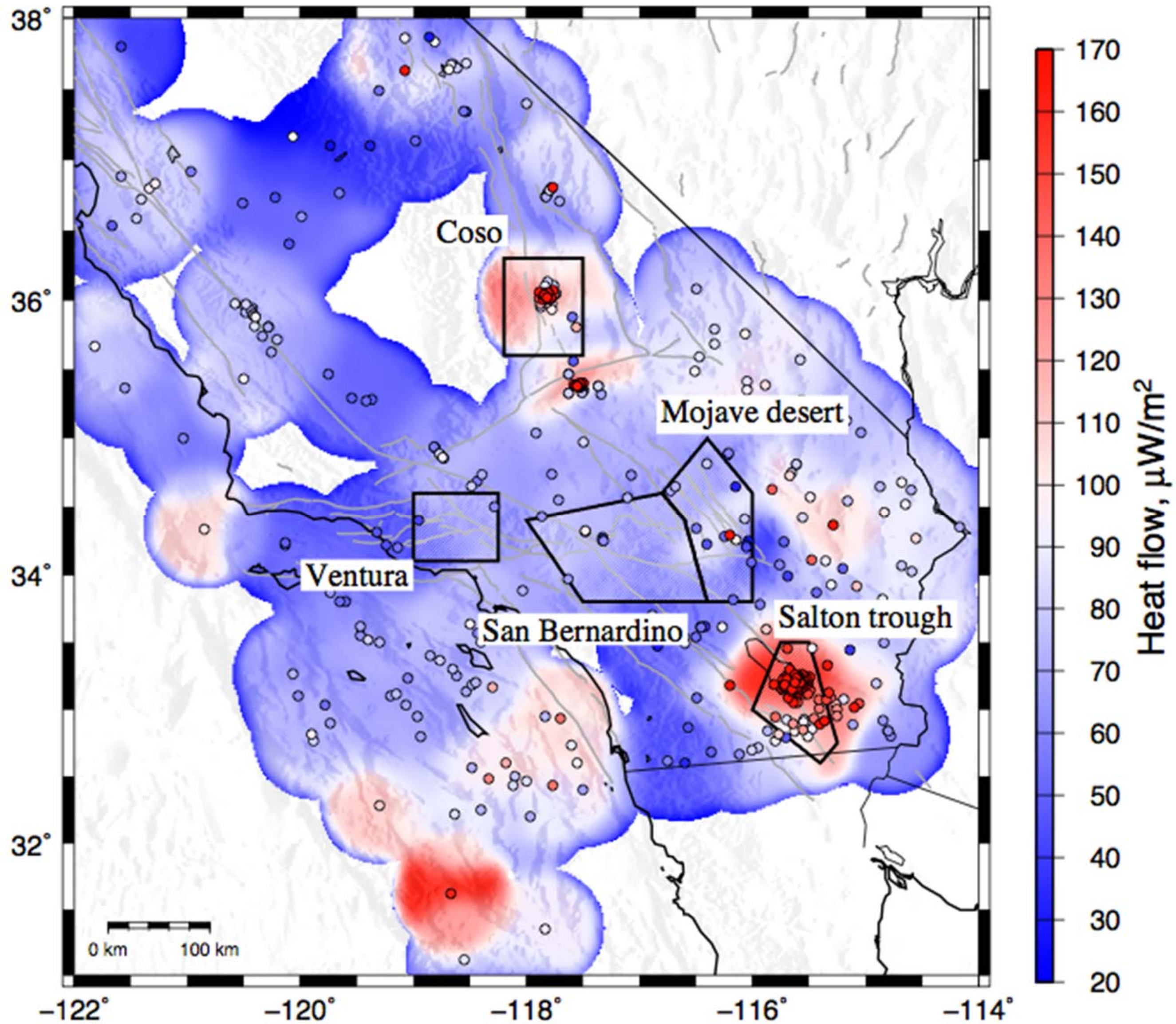


HYS (2012), $m_M \geq 2$

Cluster type
vs. physical properties of the crust

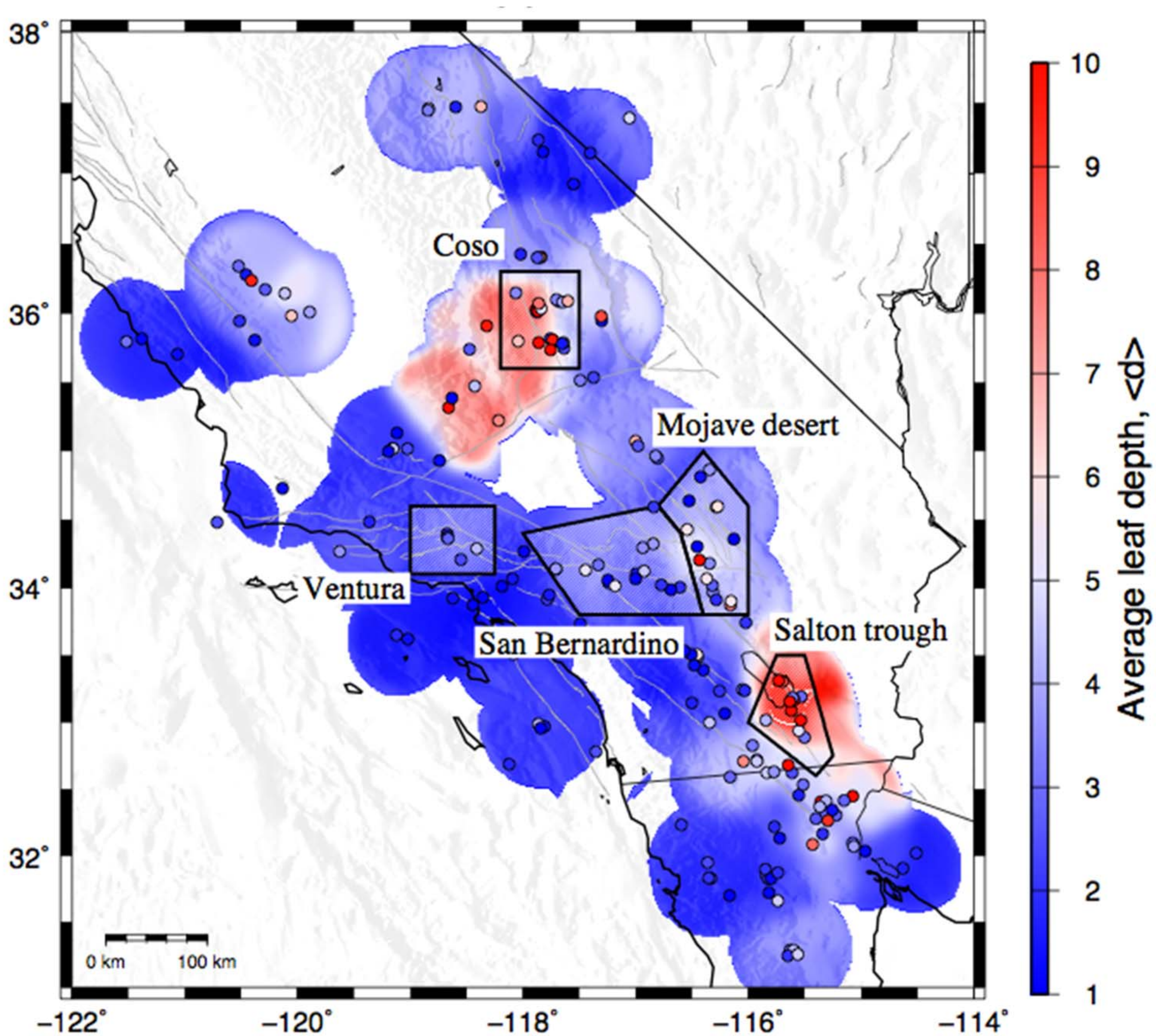
Heat flow in southern California

http://www.smu.edu/geothermal



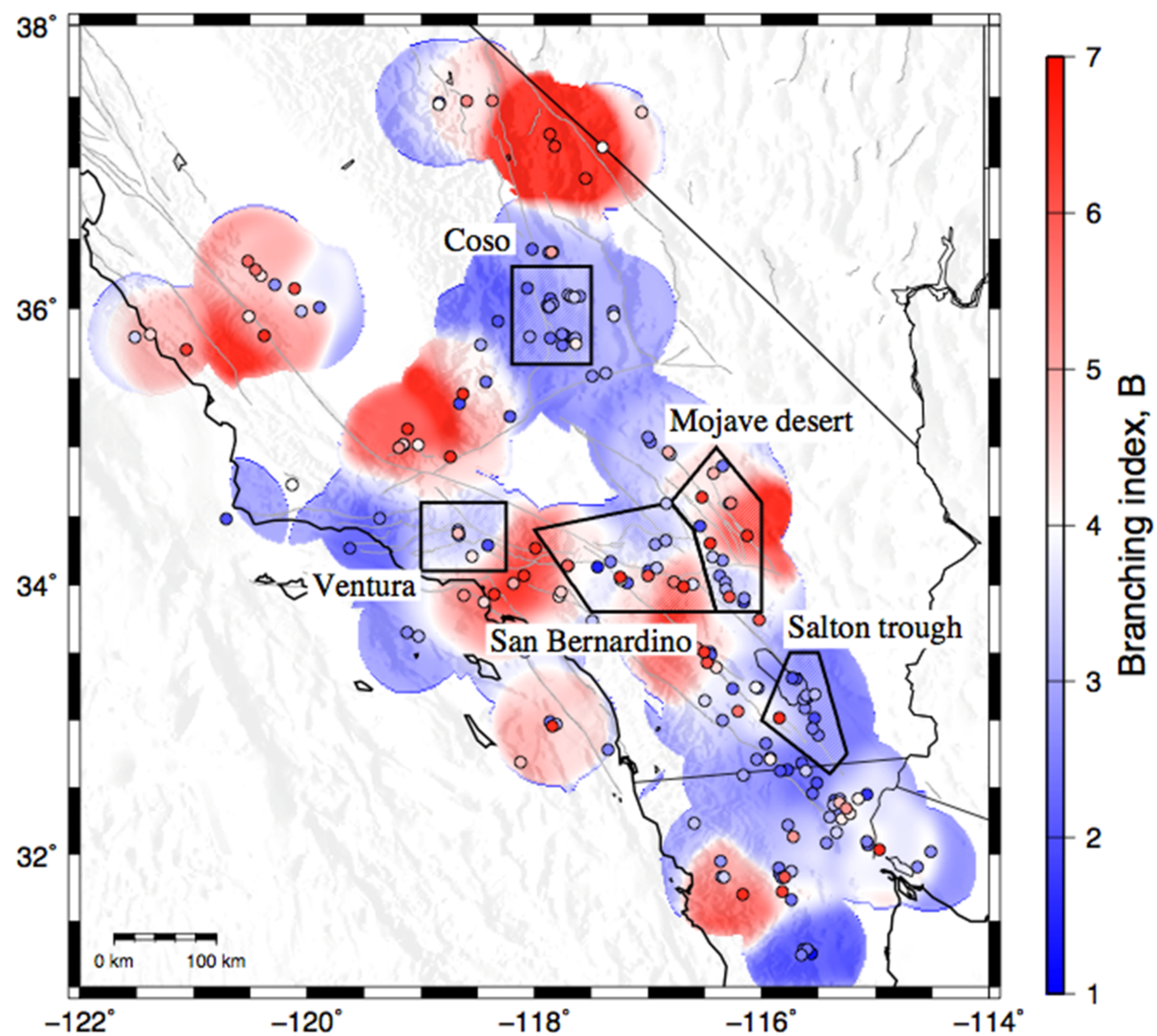
Preferred spatial location of burst/swarm like clusters

195 clusters with $m \geq 4$, $N \geq 10$; spatial average within 50 km



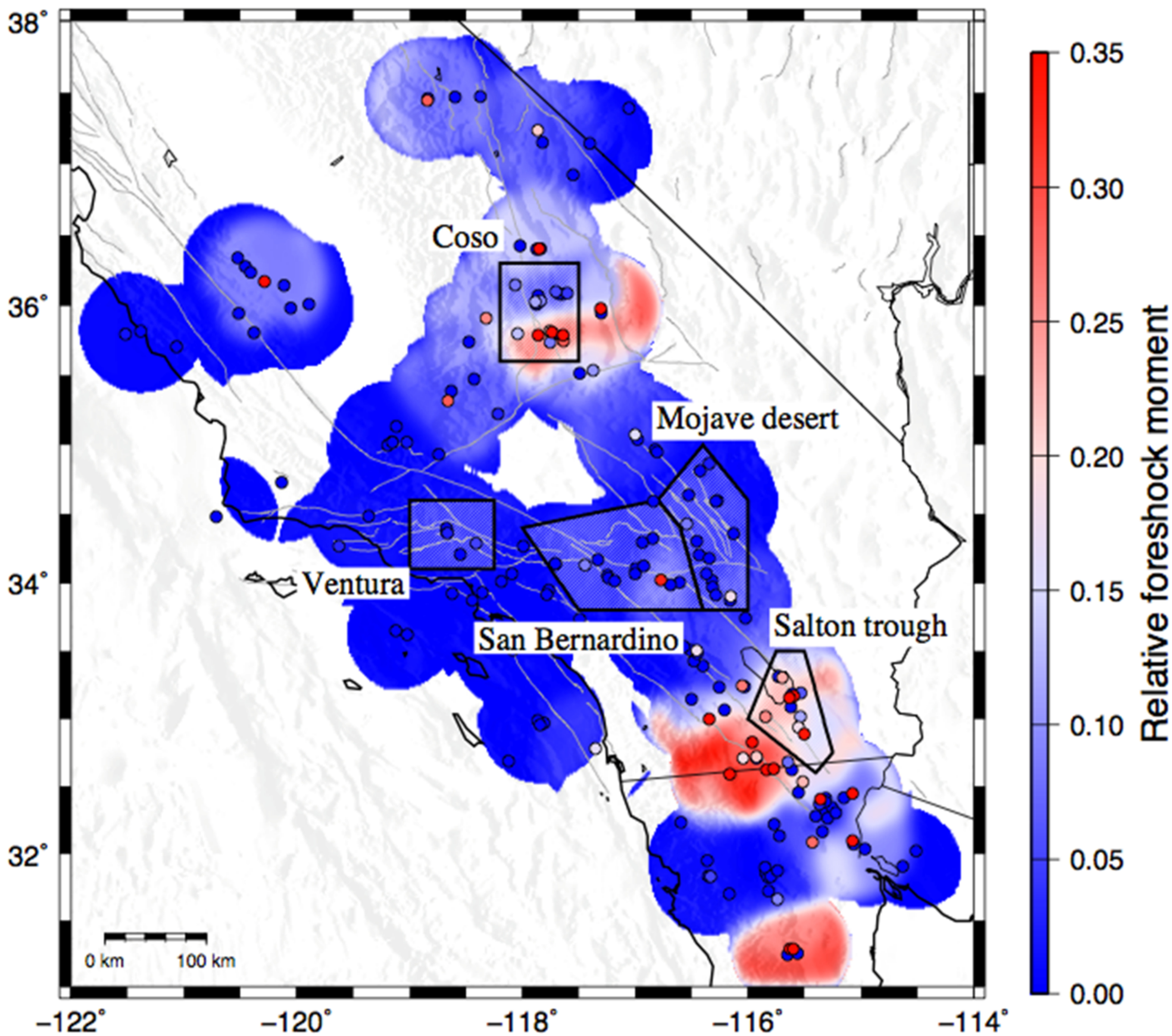
Branching index (average no. of offsprings within family)

195 clusters with $m \geq 4$, $N \geq 10$; spatial average within 50 km



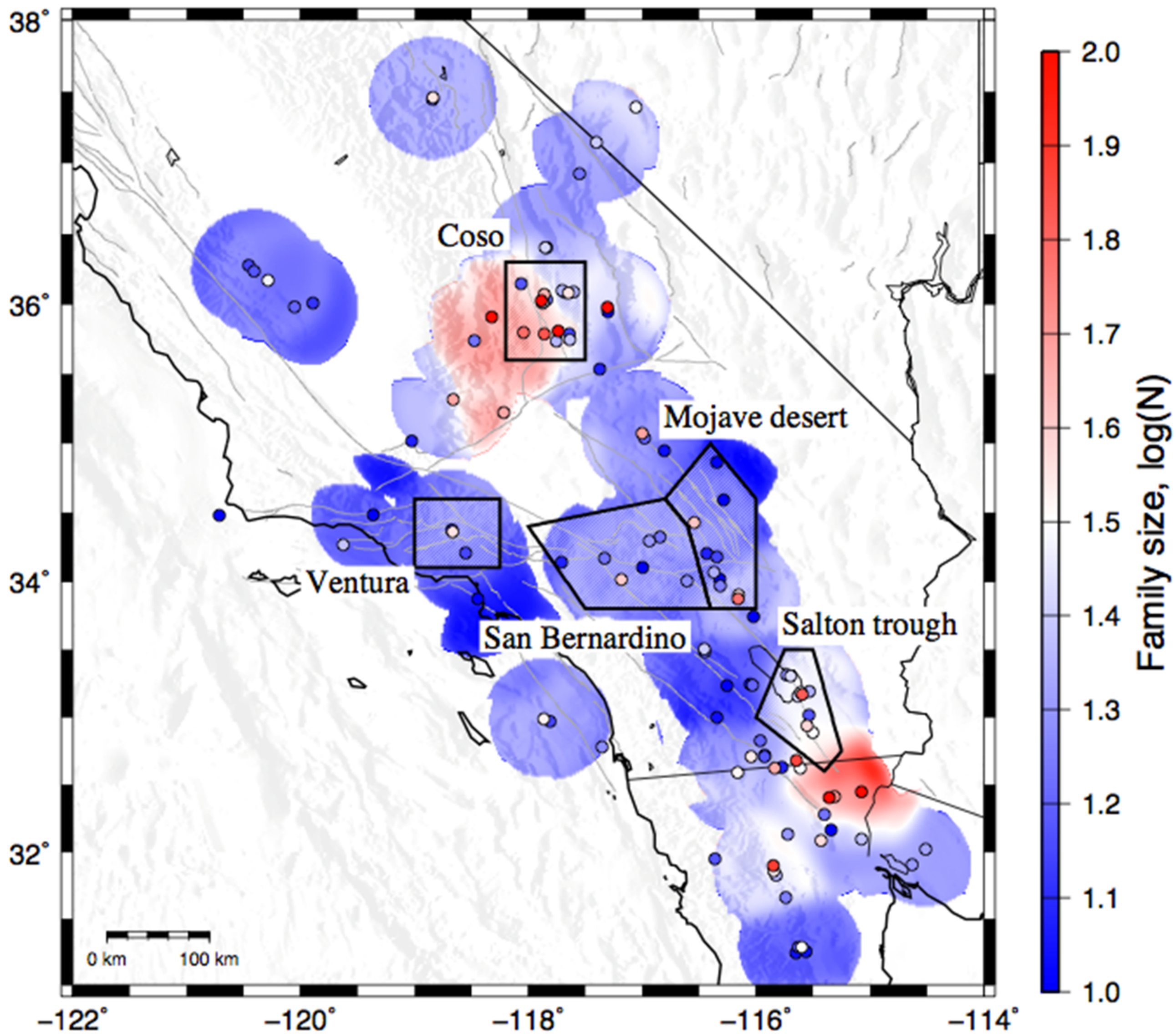
Moment of foreshocks relative to that of mainshock

195 clusters with $m \geq 4$, $N \geq 10$; spatial average within 50 km



Family size

112 Δ- clusters with $m \geq 4$, $N \geq 10$; spatial average within 50 km



ANOVA test of the null hypothesis

H_0: The average value of a family statistic S is the same in cold and hot regions

for families with mainshock magnitude $m \geq 4$

#	Statistic, *S*	*P*	Decision at 5% level
1	No. of aftershocks, N_A	5×10^{-4}	Reject
2	No. of foreshocks, N_F	1×10^{-6}	Reject
3	Relative aftershock moment, M_A/M_M	3×10^{-3}	Reject
4	Relative foreshock moment, M_F/M_M	3×10^{-6}	Reject
5	Average leaf depth, $\langle d \rangle$	3×10^{-6}	Reject
6	Maximal leaf depth, d_{max}	1×10^{-4}	Reject
7	Mainshock depth, d_{main}	2×10^{-6}	Reject
8	Branching, *B*	2×10^{-2}	Reject
9	Aftershock magnitude difference, Δ_A	2×10^{-3}	Reject
10	Foreshock magnitude difference, Δ_F	1×10^{-4}	Reject
11	Depth, *z* [km]	2×10^{-5}	Reject
12	Heat flow, [μW/m^2]	2×10^{-12}	Reject

Summary

1 Seismic clusters in southern California

- Four types of clusters:
  - Burst-like clusters
  - Swarm-like clusters
  - Singles
  - Largest regional clusters
- Topological cluster characterization

2 Cluster statistics

- Time-space-magnitude statistics are coupled with cluster type

3 Relation to physical properties of the crust

- Swarm-like clusters <-> decreased effective viscosity
- Burst-like clusters <-> increased effective viscosity
- Results consistent with damage rheology model predictions

4
4 Universality limits: to be re-thought